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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 10

BASIC METHODS FOR THE CALIBRATION OF SONAR EQUIPMENT

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A — Armor and Ordnance
Division B — Bombs, Fuels, Gases, & Chemical Problems
Division C — Communication and Transportation
Division D — Detection, Controls, and Instruments
Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1 — Ballistic Research
Division 2 — Effects of Impact and Explosion
Division 3 — Rocket Ordnance
Division 4 — Ordnance Accessories
Division 5 — New Missiles
Division 6 — Sub-Surface Warfare
Division 7 — Fire Control
Division 8 — Explosives
Division 9 — Chemistry
Division 10 — Absorbents and Aerosols
Division 11 — Chemical Engineering
Division 12 — Transportation
Division 13 — Electrical Communication
Division 14 — Radar
Division 15 — Radio Coordination
Division 16 — Optics and Camouflage
Division 17 — Physics
Division 18 — War Metallurgy
Division 19 — Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him —some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

One of the principal responsibilities placed upon Section C-4, later Division 6, when it was organized in 1941 was that of developing new and improved methods for detecting submerged submarines. Experience had shown that sound is the only form of energy which can be propagated through sea water with sufficient intensity and range to serve as a practical method for detection. For this reason the Section initiated at once a thorough study of the acoustical properties of sea water as well as of methods for injecting sound energy into the water and of detecting its presence there. Realizing that in a study of this kind accurate measurement in terms of known and reproducible standards is essential, the Section undertook early in 1941 to develop a number of standard projectors and hydrophones covering the useful frequency ranges and capable of being accurately calibrated in terms of energy output or input. Further, the Section undertook to develop methods for calibrating these standards and methods applicable to the accurate testing of underwater sound gear under development or in production by various Government agencies. This activity was at first conducted under a contract at the Bell Telephone Laboratories, which established two calibrating and testing laboratories, the first at Mountain Lakes, New Jersey, and somewhat later a second at Orlando, Florida. The facilities of these two laboratories were made available to all organizations developing or manufacturing sound gear for the Navy.

In 1942 the operation of these two stations together with the responsibility for certain further development of methods was transferred, along with many of the experienced personnel, from the Bell Telephone Laboratories to the Columbia University Division of War Research contract. The former organization, however, continued the further development and particularly the construction of standard instruments which have found wide use. From the time of transfer, the organization carrying on operations centering at Mountain Lakes and Orlando was known as the Underwater Sound Reference Laboratories and was under the direction of Dr. Robert S. Shankland.

In addition to the two above-mentioned testing stations, various of the Division's other contractors found it necessary to establish at suitable locations less elaborate testing laboratories to facilitate the testing of sonar devices, systems, and methods at various stages of their development.

The material in this report prepared by members of the staff of the Underwater Sound Reference Laboratories describes the methods and procedures which, as a result of over four years development and experience, the Division believes can be followed in establishing and operating a sound reference laboratory. The possible scope of such a laboratory is indicated by including a description of its activities since its operation under the Columbia University Division of War Research.

In addition to the persons whose names appear as authors of chapters or sections of this report, many others have made important technical contributions to this development.

The four-year program covered by this report owes much to the continuous liaison furnished by the Navy. The Division expresses its appreciation for the most helpful and cordial support and cooperation received from the Office of the Coordinator of Research and Development and from the Bureau of Ships (940). A list of the principal Navy projects is furnished on page 171.

Manufacturers producing or developing sonar material under Navy contracts have in many and various ways cooperated wholeheartedly. In particular, members of their staffs gave freely of their time to the work of the Hydrophone Advisory Committee appointed by the Office of the Coordinator in April, 1942. On page 172 the structure and the general scope of this committee are outlined.

John T. Tate
Chief, Division 6

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PREFACE

The problem of developing and establishing accurate standards and procedures for calibration of underwater sound equipment required the attention of many laboratories operating under contract with Division 6, NDRC. Although most of this work was done originally by the Bell Telephone Laboratories and later by the Underwater Sound Reference Laboratories of Columbia University, a number of other organizations contributed to the results summarized in this volume. In view of the wide scope of this field, however, it was not possible in the limited time allotted for the preparation of this volume to include a complete treatment of all of the numerous contributions. The principal reports covering this complementary work have been included in the bibliography and are preserved in the form of microfilm records.

In the preparation of this volume, the emphasis has been placed on the experience gained by Division 6 laboratories in developing testing methods and apparatus and in carrying through an extended program of precision measurements on underwater acoustic devices. The basic principles of these measurements are developed and systematized in close coordination with a description of the measuring and calibrating facilities of the test stations at Mountain Lakes, New Jersey and Orlando, Florida. It is believed that these descriptions are sufficiently complete to be of material service to other groups in setting up and maintaining similar equipment.

As the responsibility for preparing this volume was assigned by the chief of Division 6 to the staff of the Underwater Sound Reference Laboratories, the greater part of the material included is, of necessity, drawn from the experience of this group. The entire staffs of the Mountain Lakes and Orlando stations, as well as the staff of the New York office, have collaborated in all phases of the task of collecting and preparing the data upon which the present work depends. This group included: Edwin L. Carstensen, E. Dietze, W. Richard Elliott, Leslie L. Foldy, Frank H. Graham, Earle C. Gregg, Jr., Erhard Hartmann, Norma Hartmann, F. William Hoffman, Paul F. Joly, Joseph B. Keller, Martin J. Klein, L. Pauline Leighton, Lucille Northrop, Henry Primakoff, Edward S. Rogers, Robert S. Shankland, Erwin F. Shrader, D. Bernard Simmons, Richard J. Tillman.

Acknowledgement should also be made of contributions by Division 6 laboratories at the Massachusetts Institute of Technology, Harvard University, University of California, and Columbia University. In addition, valuable assistance was received from the Brush Development Company, Submarine Signal Company, the Radio Corporation of America, and the service laboratories of both the United States and British Navies.

R. S. Shankland
Director, Underwater Sound
Reference Laboratories

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Chapter 1

INTRODUCTION

By *Robert S. Shankland*

SCIENTIFIC programs generally require accurate standards and techniques of measurement to insure quantitative correlation and interpretation of phenomena under investigation. Only when an understanding of phenomena in quantitative terms has been achieved can accumulated data be effectively and efficiently applied to the design of new equipment, to the improvement of present designs, and to the prediction of results obtainable with such gear.

The program undertaken by Section C-4, later Division 6 of NDRC, included studies and experimental investigations on the transmission of sound in ocean waters and the further development of sonar gear. This necessitated the provision of suitable practical standards and a study of measurement techniques. The results accomplished form the principal subject of this volume.

In the development of apparatus for service use it is generally true that the final criterion is the effectiveness of the equipment under operational conditions. In the case of sonar gear, operational tests are not only expensive and time-consuming, but are performed at that stage in development when changes in design are most difficult to achieve. Hence, laboratory tests under controlled conditions directed toward determining design changes, which will produce maximum effectiveness under operational conditions, are a necessary adjunct to a program of research and development.

1.1 DEVELOPMENT OF MEASUREMENT AND CALIBRATION TECHNIQUES

1.1.1 Establishment of Standard Sound Fields

To make the results of the several laboratories engaged in subsurface warfare research directly comparable, it was necessary to reduce their test data to common terms. Also, as the program progressed, it was necessary to work continually toward higher standards of accuracy. The Underwater Sound Reference Laboratories [USRL] were assigned the task of establishing reference levels, and of making calibrated standards available to the other laboratories.

Originally, this standardization was based upon the characteristics of hydrophones (developed in cooperation with the Bell Telephone Laboratories, Inc. [BTL]), whose absolute calibrations could be obtained from their design or by comparison with fairly well established standards for air acoustics. Later, it was found that the reciprocity method of calibration provided improved accuracy and a simplified procedure.

The reciprocity method of calibration had been suggested by Ballantine and MacLean,[71,77] but had received little attention until it was applied to the establishment of fields in underwater sound. Its adoption by the USRL has facilitated accurate calibration of standards for frequencies ranging from about 10 c to 2.5 mc, with the possibility of attaining much higher frequencies. The lower frequency limit was determined by the difficulty of making low-frequency measurements in a shallow lake and not by failure of the reciprocity method. In the range from 100 c to 100 kc, this method is accurate to within ± 1 db. A comparison of standard levels obtained by reciprocity calibration at USRL with those independently established at British laboratories showed excellent agreement. Other calibration methods (low frequency pressure tank built by BTL and the CMF self-calibrating condenser hydrophone, built by the Massachusetts Institute of Technology [MIT]) successfully extended the low frequency limit to below 1 c.

1.1.2 Development of Standard Instruments

Although the BTL, operating under an OSRD contract, was largely responsible for the development of hydrophones and projectors suitable for use as standards, many other laboratories constructed standards suited to the particular applications in which they were interested. Instruments, employing piezoelectric crystal, magnetostrictive, condenser and electrodynamic coupling, cover collectively the 1 c

to 2.5 mc frequency range. Many of these instruments have flat responses over wide frequency ranges. The 3A type crystal hydrophone, for example, has a flat response from about 100 c to 25 kc, and the XMX crystal hydrophone has a flat response within ±2 db from below 100 c to about 100 kc and hence were useful not only for single frequency measurements, but also for recording transients, and for measuring signals covering a wide frequency band. In the majority of cases, these instruments were also characterized by mechanical ruggedness and stability of calibration. Considering the fact that acoustic standards for underwater applications were almost nonexistent before 1940, the rapidity and comprehensiveness of subsequent developments in the art are noteworthy.

1.1.3 The Objectives of Tests and Calibrations

Although the necessity for development and preproduction tests of underwater sound gear was soon recognized, the specific objectives of such tests and calibrations became apparent with further development. Although this problem is still not completely solved, much has been learned concerning the significance of the various factors which characterize efficient operation of sonar gear. Because of the large number of tests required and the limited facilities available, it was necessary to concentrate on the determination of these factors which depend upon the application for which the equipment was designed. While factors such as frequency response, directivity, impedance, signal-to-noise ratio, and efficiency were of significance in the majority of measurement programs, other quantities including rear response, side lobes, tuning, harmonic distortion, and variability with temperature and pressure often were of equal importance.

Quantitative relationships between the foregoing quantities and the operational efficiency of underwater sound devices were only imperfectly understood at the initiation of the program. Theoretical and experimental studies which were undertaken provided a more exact understanding of these relationships and a sounder basis for compromise between competing factors in design, and, in turn, a basis for the selection of important parameters to be measured in development and calibration tests. Thus, the relationship which existed between development, calibration and testing, and operational and tactical application of the equipment, was of inestimable value in unifying the program as a whole, and in directing it toward its prime objectives.

1.1.4 Testing Technique

With reference standards available, and with increased knowledge of significant parameters, the technique of actually performing a calibration test remained to be considered. Because these parameters were characteristic of the devices under test, and had to be distinguished from extraneous effects produced by the test location and by the equipment involved, a large part of the effort of the USRL, as well as that of other laboratories engaged in equipment development, was directed toward devising measurement techniques. The principal problems in testing gear in laboratory sites arise from the limited extent of the testing medium. Acoustic reflections from the surface, bottom, and shores of the body of water in which the tests are made and the limited testing distance available required the development of means for eliminating the effect of these factors. To this end baffles and screens, directional sources, proper orientation of instruments, pulses and noise bands have been used for eliminating the effect of reflections, and spherical wave corrections have been applied to compensate for effects caused by short testing distance. In addition, equipment was designed to reduce the time and labor necessary for performing tests with maximum use of available facilities. Among devices in this category are automatic recorder devices (linear and polar), special amplifiers, arrangements for rapid changes in driving and receiving impedances, adjustable and interchangeable rigging gear, and computing aids to facilitate the reduction of data. Techniques for testing in indoor tanks under varying conditions of temperature and pressure, for testing at high power inputs, and for measuring impedance under various conditions were developed as the need arose. With experience, the technique of testing underwater sound devices grew as an art as well as a science. Close liaison with developments in the field of underwater sound was essential to insure the adaptability of testing techniques and facilities. This flexibility made possible the realization of the potentialities of laboratory testing in the development of underwater sound devices.

1.2 ROLE OF PRECISION ACOUSTIC MEASUREMENTS IN THE IMPROVEMENT OF UNDERWATER SOUND EQUIPMENT

1.2.1 Improvements in Transducer Design

An example of the importance of precision acoustic measurements and fundamental research in improving sonar gear is afforded by developments in transducer design and construction in the period 1940–1945. Two types of electroacoustic coupling, magnetostrictive and piezoelectric, had been found most useful. Fundamental investigations of magnetostrictive phenomena conducted by Division C, Navy, and industrial laboratories have greatly increased knowledge of the source of power losses in magnetostriction transducers. Application of this knowledge led to a 400 per cent increase in transducer efficiency. This increase in efficiency not only markedly improved operation but also greatly reduced the bulk, cost and critical materials requirements of the equipment.

Improvement in equipment using piezoelectric crystal coupling closely parallels that obtained for magnetostrictive equipment. Thus, initial efficiencies of the order of 10 to 20 per cent have been increased to values as high as 75 to 80 per cent.

Improvements in transducers have not been limited to increased efficiency. The development of ammonium dihydrogen phosphate [ADP] crystals made possible crystal transducers with negligible temperature dependence and, more important, with ability to withstand greater temperature extremes without damage. Furthermore, new construction methods for both crystal and magnetostriction transducers made possible the fabrication of transducers with special characteristics. Many other examples of specific improvement are available to demonstrate the importance of fundamental research.

1.2.2 Improvements in Dome Design

In 1942, one of the most pressing sonar problems was that of designing domes which, when mounted on vessels, would not hopelessly distort the directional patterns of the transducers they enclosed. Internal reflections from the walls of domes, then available, were nullifying the effort to attain satisfactory directional patterns. This effect, together with the high transmission loss through the dome wall sharply reduced the effectiveness of the equipment. British experience in meeting this problem, coupled with an experimental research program on domes at the Naval Research Laboratory, at Division 6 NDRC laboratories, and at the Bell Telephone Laboratories, supplemented by theoretical research, in which the Division was given invaluable assistance by the Applied Mathematics Panel, effectively demonstrated the principles necessary to reduce internal reflections to a negligible amount. On the basis of these principles, various manufacturers were able to produce acoustically satisfactory domes with high mechanical strength without a corresponding increase in thickness of the dome wall. The solution of the dome problem during 1943 was so effective that dome construction was never again a major problem.

1.3 FUNDAMENTAL STUDIES AND OPERATIONAL PERFORMANCE OF UNDERWATER SOUND EQUIPMENT

1.3.1 Relation to Calibration and Test Measurements

It has previously been stated that the goal of antisubmarine research is improvement in the operational performance of gear. The relation of fundamental studies to operational performance is largely indirect and finds expression in their influence on development. One of the purposes of these studies has been to determine the relation between the parameters (power output, response, directivity, signal-to-noise ratio, etc.) of underwater sound gear to its effectiveness in operation. This relationship is important, as it helps determine by laboratory measurements on the gear itself its probable operational effectiveness. Such a technique provides many advantages, including: (1) efficiency of time and effort, (2) closer liaison with development work, (3) the possibility of making tests under controlled conditions, at any time, and (4) clearly defined conclusions from tests.

1.3.2 Relation to Development of Equipment

These studies reveal, also, important information bearing on the equipment design. In evaluating the relationship between gear parameters and opera-

tional performance, they indicate the relative importance of the parameters and thus establish the changes in design most effective for improving operational performance of the gear. As desirable improvements are often inherently contradictory, these studies may be useful in indicating the most advantageous compromise, not only for gear in general, but in view of particular conditions of service, and also for particular types of equipment.

The studies have been carried out on a more comprehensive basis directed toward evaluating the relative effectiveness of different classes of gear by information obtained in controlled surroundings.

1.3.3 Relation to Manufacturing Requirements and Specifications

There is still another important application of fundamental calibration measurements on underwater sound gear, namely, as an aid to the establishment of manufacturing acceptance requirements. Whenever it is necessary to manufacture equipment in production quantities, it is often impossible, because of considerations of time and facilities available, to test completely each unit produced. It is therefore necessary to examine critically those factors of prime importance in determining satisfactory operation of the equipment, and to establish limits of acceptable performance. These limits should be primarily based on careful studies of the gear under controlled conditions, keeping always in mind the influence of the various factors on operational performance.

Thus calibration measurements under controlled conditions not only are an aid in determining specifications but also suggest methods for determining whether manufactured equipment is within the limits set by the specifications.

Chapter 2

OPERATION AND APPLICATION OF UNDERWATER SOUND DEVICES

By *Leslie L. Foldy*

CALIBRATION work in underwater sound is concerned primarily with devices which convert electric energy into acoustic energy (projectors) and, conversely, those which convert the energy of a sound field into electric energy (hydrophones). Generically, these devices are known as electroacoustic transducers. To provide a suitable background for the detailed discussion of the problems involved in calibrating transducers, this chapter presents a brief discussion of (1) the physical principles underlying the action of transducers, and (2) their uses.

2.1 PRINCIPLES OF OPERATION OF TRANSDUCERS

As already noted, energy conversion is the fundamental purpose of transducers.[a] Most transducers can convert energy in either direction, that is, they are reversible. According to the nature of the physical process used in the energy conversion transducers may be classed under four general headings, namely electrodynamic, electrostatic, piezoelectric, and magnetostriction. The principles involved in each are discussed here in a qualitative manner. A more quantitative treatment is given in Chapter 3.

The simplest example of an electrodynamic transducer is a moving-ribbon instrument (Figure 1) which consists of a rectangular metallic strip or ribbon suspended in a magnetic field. When the instrument is in a sound field, there is generally a difference in pressure established between its front and back. Since the mass of the ribbon differs from that of the magnet, relative motion of the two results, inducing an electromotive force in the moving ribbon. Conversely, if an alternating current flows through the suspended ribbon, the forces on it due to interaction of the current and the external magnetic field produce vibration. This vibratory motion in turn creates a sound field in the medium. Since the process depends on the pressure difference between the front and back of the ribbon, such an instrument is called a pressure-gradient hydrophone.

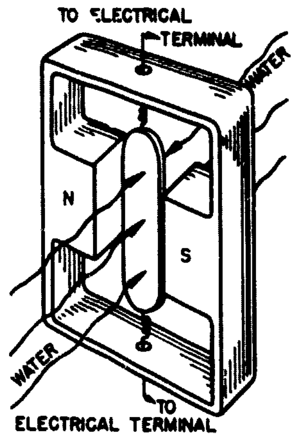

FIGURE 1. Electrodynamic transducer (pressure-gradient type).

Electrodynamic transducers in which operation depends on the value of the pressure at a point in the medium, rather than on the gradient of the pressure, may also be considered. A simple example is a transducer containing a diaphragm mounted in a watertight housing in such a manner that only one of its faces is exposed to the water (see Figure 2), and with the pressure in the housing adjusted to compensate for the external hydrostatic pressure. A coil encircling a fixed magnet is rigidly fastened to the unexposed

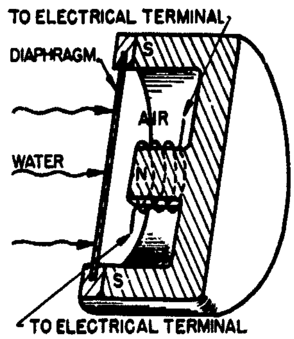

FIGURE 2. Electrodynamic transducer (pressure type).

[a] These matters are discussed in detail in the Division 6 volumes on magnetostriction and crystal transducers.

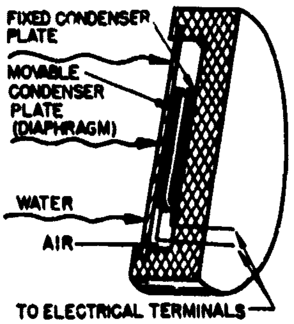

FIGURE 3. Electrostatic transducer.

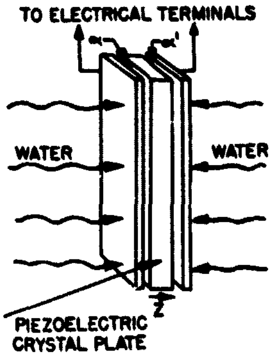

FIGURE 4. Piezoelectric transducer.

side of the diaphragm. When the instrument is placed in a sound field, the diaphragm and coil are set into vibration relative to the magnet. This vibration changes the flux linked by the coil, thus inducing an alternating emf in it. Conversely, the force due to the interaction of an alternating current through the coil and the field of the magnet gives rise to vibrations of the coil and diaphragm, generating a sound wave in the medium.

Electrostatic, piezoelectric, and magnetostriction transducers are generally pressure rather than pressure-gradient instruments. Thus, a condenser-type transducer uses an electrostatic field to convert acoustic into electric energy and vice versa. An example of the condenser-type instrument is shown in Figure 3. Here a constant potential is applied between the plates of the condenser. When the instrument is placed in a sound field, the movable plate is set into vibration with respect to the fixed plate. This vibration changes the distance between the plates, and consequently the capacity, of the condenser. Since the voltage across the plates is inversely proportional to the capacity, an alternating voltage is generated. Conversely, the application of an alternating electric potential to the plates changes the force between them, and consequently causes vibration of the movable plate.

The other two types of reversible transducers depend on less familiar physical phenomena. The first of these is the piezoelectric effect. It has been found that certain crystals, when subjected to compression, exhibit electric charges on their faces; under tension the charges are reversed. The inverse piezoelectric effect also exists: the crystals expand when a potential of one sign is applied across the faces and contract when an opposite potential is applied.

The faces on which the charges appear when the crystal is subjected to stress depend on its structural properties. A tourmaline crystal, for example, is one of the simplest insofar as piezoelectric effects are concerned. Tourmaline possesses a single piezoelectric axis such that a stress in the direction of this axis produces charges on the faces normal to it. Thus, in Figure 4, if a stress is applied in the direction of the piezoelectric axis Z, charges appear on the faces α and α'. Conversely, applying a potential between α and α' causes the crystal plate to expand or to contract in thickness (depending on the sign of the potential) in the Z direction.[b]

The simplest type of piezoelectric transducer, therefore, comprises a tourmaline crystal in contact with two metal condenser plates. Application of an alternating potential to the plates causes the crystal alternately to expand and contract. Upon immersing the system in water, a sound field is generated by the vibration of the plates. Conversely, vibrations produced by placing the crystal and condenser plates in a sound field give rise to an alternating voltage on the plates.[c]

The fourth type of transducer, shown in Figure 5, operates on the principle of the magnetostrictive effect, which bears certain similarities to the piezoelectric effect. If a rod or tube of ferromagnetic material (iron, cobalt, nickel, or various alloys containing

[b] The changes in length involved are small. For tourmaline, the fractional change in length per unit electric field (1 volt per cm) is 1.93×10^{-10} cm$^{1/2}$ gm$^{-1/2}$ sec.

[c] It may be remarked that the amplitude of vibration for a given impressed alternating voltage and the magnitude of the induced alternating voltage for a given impressed sound field are both maximized when the frequency of the impressed voltage, or sound field, coincides with the natural mechanical resonance frequency of the crystal.

these metals) is brought into a magnetic field parallel to its length, its length is changed slightly.[d] This change of length is independent of the sign of the field and may be either an increase or decrease, depending on the nature of the material, its previous treatment, the degree to which it was previously magnetized, and the temperature. This phenomenon is reversible: in other words, if a previously magnetized rod of nickel is stretched, the magnetization of the rod is decreased; if the same rod is compressed, the magnetization is increased.

If a coil of wire is now put around the rod, an emf is induced in it by the changes in the magnetic flux caused by the elastic deformation. In a similar manner, changes in the rod's magnetization due to an external alternating current induce periodic oscillations in its length.[e]

This simple magnetostriction transducer is, in effect, a rod of ferromagnetic material surrounded by a coil.

It should finally be pointed out that there are, in addition to the reversible transducers which have been considered, irreversible ones. In the carbon microphone, for example, changes in pressure on a diaphragm caused by an impinging sound field produce changes in the electrical resistance of contacts between carbon particles and give rise to an alternating current, provided that a source of constant potential is present.

2.2 DIRECTIVITY OF TRANSDUCERS

The variation with direction of the emitted sound intensity, referred to the transducer acoustic axis,[f] is called the directivity of the transducer on transmitting. In a similar manner, the directivity of the transducer on receiving is defined as the variation of the output voltage for a plane-wave sound of given in-

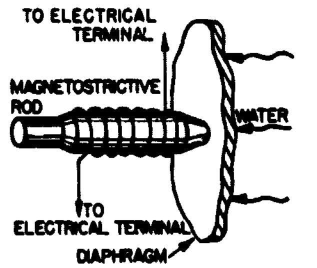

FIGURE 5. Magnetostriction transducer.

tensity incident in various directions with respect to the axis.

Directivity on transmitting results from the superposition at a point in space of sound wavelets emitted by different portions of the diaphragm, and consequently having different amplitude and phase. On reception the directivity is the result of the incidence on different portions of the transducer diaphragm of wavelets of sound which have, at the diaphragm, different amplitudes and phases depending on the orientation of the diaphragm relative to their direction of propagation.

In general, the directivity, both on transmitting and on receiving, is determined by the ratio of the sound wave length to the diaphragm dimensions.[g] For a plane piston diaphragm with dimensions large compared to a wave length, the transmitted sound field is, at large distances from the transducer, centered about the transducer acoustic axis, and the sound is emitted in the form of a "searchlight" beam. Conversely, on reception, the transducer is sensitive only to sound signals incident in directions close to and along the axis. Subsidiary maxima (side lobes) in directions far from the axis usually are present. These, however, are strongly dependent on the exact velocity distribution along the diaphragm, and are customarily small compared with the main or searchlight beam.[h] If the wave length is large compared to the diaphragm dimensions, the sound is emitted uniformly in all directions. In this case, the transducer response on reception is independent of the direction of sound incidence. An intermediate case is a "line"

[d] The fractional change in length is approximately ten parts in a million for fields up to 1,000 gauss.

[e] It is to be noted that, since the increase or decrease in length of the magnetostrictive rod is independent of the sign of the magnetic field, an originally unmagnetized rod vibrates at twice the frequency of the impressed field, while a rod which has been sufficiently magnetized by another constant (polarizing) field vibrates at the impressed frequency. Maximum amplitude occurs when the impressed and natural frequencies of vibration coincide.

[f] The transducer acoustic axis is arbitrarily selected, but is usually chosen to be an axis of symmetry of the instrument, such as the normal to a plane vibrating diaphragm.

[g] Transducers obeying the reciprocity theorem (see Chapters 3, 4, and 5) have the same directivity on transmitting and on receiving.

[h] By constructing a transducer with a plane diaphragm and with a velocity distribution which is greatest at the center of the diaphragm and which decreases toward the edges (shading), it is possible to obtain a directivity distribution with side lobes much smaller than in the case of a constant velocity distribution; the width of the main beam is, however, larger in this case.

transducer, with a pulsating cylindrical surface of a length which is large, and a diameter which is small, compared to a wave length. Here the sound is emitted uniformly in all planes containing a cross section of the cylinder, while in perpendicular planes the sound is concentrated in a beam.

2.3 APPLICATION OF UNDERWATER SOUND DEVICES

The applications of underwater sound devices in naval operations may be roughly divided into two categories: tactical and nontactical.[1] Tactical applications include the detection of surface vessels, submarines, torpedoes, mines, and underwater phenomena by surface vessels and submarines. The nontactical applications include: fathometer depth determinations by surface craft and submarines; monitoring of noise output by submarines; underwater communication by code or voice; fundamental studies on sound propagation in the ocean, on ship noises, on underwater phenomena, etc., designed to aid in the tactical employment of sonar devices; and finally the calibration of sonar gear with standard projectors and hydrophones.

2.3.1 Tactical Applications

Tactical applications of sonar gear generally involve either echo ranging or listening. In echo ranging, the devices emit either a pulse or a continuous-wave signal, which may be of either sonic or supersonic frequency. If the signal strikes a target, part of its energy is reflected back to the emitting device (the projector) which receives the signal. On the basis of characteristics such as frequency shift and time delay between emission and reception, conclusions may be drawn regarding the range, bearing, speed, and nature of the target. In listening, any supersonic or sonic signal or noise emitted by a target actuates a receiving device which, from the characteristics of the signal or noise (intensity, frequency, and direction), enables conclusions to be drawn regarding the range, speed, bearing, and nature of the target.

Echo-Ranging Gear

Conventional searchlight echo ranging gear as employed in the last war may be classified according to its tactical use, as *antisubmarine* or ***prosubmarine***. Searchlight-type gear is in general use in both the United States and British Navies. Searchlight-type echo-ranging gear consists of a projector with either a square or a circular diaphragm operating on the piezoelectric or on the magnetostrictive principle. The dimensions of the projector are, as a rule, considerably larger than the wave length of sound emitted, so that a relatively narrow beam is formed. The axis of this beam may be rotated by training the projector in a horizontal and sometimes in a vertical plane. As a result of the application of a suitable pulse voltage, the projector emits supersonic pulses of from 10 to 200 milliseconds duration.

Immediately after transmission, the projector is switched from the transmitter to the receiver. Any received reflected pulse of supersonic frequency is either directly rectified and presented visually on the screen of a cathode-ray tube or, more customarily, is heterodyned to an audible frequency and presented through a loud-speaker. The time delay between transmission and reception is a measure of the range of the target from the projector; the orientation of the projector (or beam) axis in space at the instant of transmission gives the relative bearing of the target; any difference between the frequency of the emitted and the received pulse (the Doppler effect) is a measure of the speed of the target; and the quality of the received (heterodyned) pulse often throws information upon the nature of the target (for example, distinguishes a submarine from its wake). Thus, considerable information about the position, motion, and nature of the target is obtained.

By systematically training the projector in azimuth (i.e., by following a definite search plan) it is possible to sweep a sector of ocean where the presence of the target is either known or suspected. In echo ranging by surface craft in search of submarines, the target may be found at different depths and ranges so that the width of the beam of the main projector is not always adequate for maintenance of contact. In this case, auxiliary projectors may be employed.

A list of representative tactical applications of various searchlight echo-ranging devices follows:

1. Detection of submarines by surface craft.
2. Detection of submarines by harbor installations.
3. Detection of submarines and surface craft by submarines.
4. Detection of small objects such as mines, tor-

[1] The distinction between tactical and nontactical applications is, of course, rather arbitrary and by no means rigid.

pedoes, landing obstacles, and shoals by surface craft, submarines, and swimmers.

Listening Gear

The second tactical application of sonar gear involves listening, in which any supersonic or sonic signal or noise emitted by the target and reaching the hydrophone[j] is picked up and presented to the operator. If the incident signal is not of an audible frequency to begin with, the resultant hydrophone output may be heterodyned to an audible frequency. Intensity, frequency, and direction of incidence of the signal enable conclusions to be drawn regarding the nature, speed, range, and bearing of the target. In particular, if a directional hydrophone[k] is used, the bearing of the target may be determined from the direction of orientation of the hydrophone axis at the position of maximum response.

The following specific tactical applications of listening may be listed:

1. Sonic and supersonic listening for submarines from antisubmarine craft, harbor installations, other submarines, and expendable devices, sono buoys, etc.[l] Supersonic listening is perhaps preferable to sonic listening in these cases because of the high directivity generally obtainable with supersonic gear.[m] Supersonic hydrophones on antisubmarine craft, harbor installations, and submarines can also pick up the emitted echo-ranging pings of enemy submarines.

2. Sonic and supersonic listening for surface craft from submarines. Sonic and supersonic listening, usually with more or less directional hydrophones, is widely used by submarines to detect the noise output of merchant craft in convoys, of antisubmarine craft, and of other enemy warships. Submarines also often overhear on supersonic listening gear the echo-ranging pings of antisubmarine craft.

3. Supersonic listening for torpedoes from surface craft and submarines. Cavitation noise from a moving torpedo may be detected by directional supersonic listening gear, and appropriate evasive action may be taken.

[j] Hydrophones used in practice are of a variety of constructions, sizes, and shapes, but usually operate on the piezoelectric or magnetostrictive principle.

[k] The directional receiving hydrophone may be the projector of the supersonic echo-ranging gear, hooked up electrically for signal reception.

[l] A sono buoy is a device containing a hydrophone and a radio transmitter. When the hydrophone receives a signal from a target (the submarine), it is transmitted by means of a radio link to patrolling antisubmarine air or surface craft.

[m] The high directivity is desirable for two reasons: it leads to a greater bearing accuracy and minimizes the self and ambient noise pickup of the gear.

2.3.2 Nontactical Applications

Nontactical applications of sonar gear include the use of standard projectors and hydrophones for the calibration of other kinds of sonic and supersonic devices,[n] the determination of physical parameters of sonar devices, and analysis of the physical parameters of a particular type of gear to determine its suitability for the tactical or other purpose at hand. A somewhat related nontactical application is the use of standard projectors and hydrophones for testing echo-ranging and listening gear installed on antisubmarine craft and on submarines, and for permitting a submarine to monitor its own sonic and supersonic output.

Other nontactical applications of sonar gear include fathometer depth determination by surface craft and by submarines. Fathometer gear, similar in construction and operation to supersonic searchlight echo-ranging gear, emits short supersonic pulses, and then receives and mechanically records reflections from the ocean bottom. Sonar gear (standard hydrophones and projectors) may also be used to study the sound output of disturbances as well as to determine the sound-absorbing and reflecting properties of various materials. A further nontactical application of transmitting projectors and receiving hydrophones involves the use of code or speech-modulated supersonic signals for underwater communication between surface and subsurface craft.

Finally, an important nontactical application of sonar gear involves its use in fundamental studies of sound propagation in the sea under various oceanographic, surface, and bottom conditions, with the attendant study of surface and bottom reflection, refraction, attenuation, scattering, and reverberation. The study of various types of noise background (ship's noise, ambient noise, and target noise) and of the reflecting power of various targets should be mentioned in this connection. Such fundamental studies are useful in determining the relation of gear operational efficacy to gear parameters with a view toward optimum sonar design.

[n] Calibration usually involves the determination of the axis response, directivity, efficiency, and power output of the device. (See Chapter 4.)

Chapter 3

GENERALIZED THEORY OF ELECTROACOUSTIC TRANSDUCERS

By *Leslie L. Foldy* and *Henry Primakoff*

3.1 INTRODUCTION

FOLLOWING the qualitative discussion of various simple idealized transducers given at the beginning of the preceding chapter, a generalized theory of linear passive electroacoustic transducers is now developed. Attention is centered on deriving relationships true for all linear passive transducers, rather than on a detailed analysis of particular types. There is a rather complete analogy between the theory of electroacoustic transducers, taking into account the properties of the sound field, and that of electromechanical transducers,[39] where only one mechanical degree of freedom is present. Consequently, this discussion is carried through in fairly abstract terms, insofar as this can be done without undue mathematical complexity. Analogies are pointed out as they occur.

An electroacoustic transducer is a device for transforming electric energy into acoustic energy, or vice versa. If all the energy delivered by the transducer to the electric or acoustic systems to which it is connected is derived from power absorbed by the transducer from these systems, the transducer is said to be passive. This does not prohibit the presence of active internal sources of power such as are used to provide polarizing voltages and currents in some types of transducers, provided that these internal sources do not supply power to the electric or acoustic systems to which the transducer is connected.

Schematically, an electroacoustic transducer may be represented as a pair of electric terminals, by means of which connection to electric systems is made, and a closed surface[a] which is in contact with a medium capable of propagating sound. The simpler electromechanical transducer, which may be represented schematically by a box with a pair of electric terminals and a pair of mechanical terminals, is shown in Figure 1.

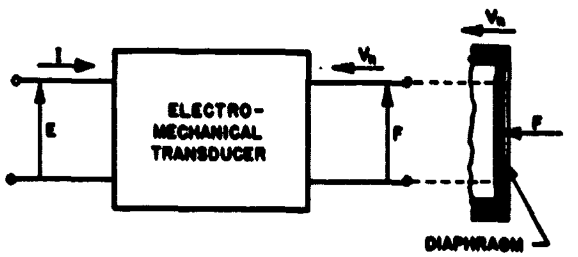

FIGURE 1. Electroacoustic transducer represented as a four-terminal electromechanical network.

Only those transducers are considered in which the acoustically active part of the surface, the diaphragm, vibrates in such a manner that its normal velocity is the same at all points (rigid vibration). It is possible to remove this restriction and develop the theory for any type of vibration, as discussed briefly later. The former case, however, is considerably simpler mathematically and the treatment of it given here contains the essential physical principles of the problem.

The quantities of interest, expressed as functions of time t, are the following: the voltage $E(t)$ across the electric terminals of the transducer, the current $I(t)$ into the electric terminals, the normal velocity $v_n(t)$ of the diaphragm, and the total force $F(t)$ on the diaphragm. This total force may be considered as the integral over the diaphragm of the pressure at each point on its surface. The pressure and particle velocity of the sound field at any point in the medium are also of interest.

Consider only the steady state, where all quantities vary harmonically with the time with the same frequency: $E(t) = E\,e^{j\omega t}$, $v_n(t) = v_n\,e^{j\omega t}$, etc. For electroacoustic transducers in which the diaphragm vibrates rigidly, it is found that any two of the four quantities E, I, F, and v_n determine the values of the other two. Take I and v_n as independent variables. The most general equations for a linear transducer of this type are then

$$F = z_0\,v_n + k\,I \tag{1}$$

and

$$E = k'\,v_n + Z_b\,I, \tag{2}$$

[a] Only part of this surface need be acoustically active.

where z_0, k, k', and Z_b are independent of E, I, F, and v_n but are in general functions of frequency.[b] Equations of the type of (1) and (2) have been shown to apply to the majority of electroacoustic transducers now in use, at least for limited ranges of the variables.

Considering the physical significance of the terms in equations (1) and (2), it is seen that z_0 is the force on the diaphragm divided by the velocity when the current is zero. Let z_0 be the open-circuit mechanical impedance of the transducer. The constant k gives the force developed per unit current into the transducer when the diaphragm is completely constrained ($v_n = 0$). Therefore k is called the electroacoustic transfer constant. Similarly, k', the open-circuit voltage per unit diaphragm velocity, is called the acoustoelectric transfer constant. The term Z_b gives the voltage developed for unit current when the diaphragm is constrained from moving and so is called the blocked electric impedance.

The equations for a simple electromechanical system are of precisely the same form as equations (1) and (2). This is to be expected, since the assumption that v_n is constant reduces the problem to one mechanical degree of freedom. The acoustic case, however, includes the properties of the sound field, as discussed below.

3.2 COUPLING CONDITIONS

Consider now the relationships which obtain when an electroacoustic transducer is coupled to electric elements or to a medium capable of propagating sound. When the transducer is used to convert acoustic energy into electric energy, it is terminated in an electric impedance Z_L, that is, there is a load impedance Z_L across its electric terminals. In that case at all times

$$E = -Z_L I. \tag{3}$$

When the transducer is used to convert electric energy into acoustic energy, a source of voltage E_0 of internal impedance Z_{int} is connected to the electric terminals. Then

$$E = E_0 - Z_{\text{int}} I. \tag{4}$$

The problem of coupling on the acoustic side may be treated formally in a similar manner. When the transducer converts acoustic energy into electric energy, we may write

$$F = F_0 - z_r v_n. \tag{5}$$

The interpretation is somewhat more complicated in this case: The term F_0 really consists of two parts, $F_0 = F_{\text{inc}} + F_{\text{rigid diffr}}$. The first, F_{inc}, is the force on diaphragm that would be present if the transducer had no effect on the incident sound field. The second part, $F_{\text{rigid diffr}}$, may be considered as representing the force on the diaphragm due to the sound that would be diffracted by the transducer if the latter were perfectly rigid. The symbol z_r represents the radiation impedance, and the term $(-z_r v_n)$ is the force on the diaphragm due to the additional sound pressure created by the latter's motion in the sound field.

Finally, when the transducer is used to convert electric energy into acoustic energy, there is no external sound field and the equation becomes

$$F = -z_r v_n. \tag{6}$$

It should be noted that equation (5) corresponds to the equation for an electromechanical transducer coupled to a source of generated force F_0 and of internal mechanical impedance z_r.

3.3 IMPEDANCES

The next problem is the determination of the effective impedances, electric and acoustic, of the transducer under various conditions of coupling. Begin with the effective electric impedance, defined as the ratio of voltage to current E/I. The value of this impedance depends on the nature of the acoustic coupling. Consider the case of the transducer in an infinite source-free medium. Then the force on the diaphragm is given in terms of the normal velocity v_n on the surface by equation (6) as $F = -z_r v_n$.

Substituting (6) in equations (1) and (2), we find

$$-z_r v_n = z_0 v_n + kI \tag{7}$$

and

$$E = k' v_n + Z_b I. \tag{8}$$

Solution of these equations shows that the effective electric impedance Z_{el} is given by

$$Z_{el} = \frac{E}{I} = Z_b - \frac{kk'}{z_0 + z_r}. \tag{9}$$

[b] The linearity of the equations insures the possibility of treating functions with any time dependence by superposition using Fourier analysis.

The difference between Z_{el} and Z_b is called the motional impedance Z_m. Thus

$$Z_m = Z_{el} - Z_b = -\frac{kk'}{z_0 + z_r}, \tag{10}$$

Z_m being the contribution to Z_{el} which results from the motion of the diaphragm.

Consider now the effective acoustic impedance z_{ac}, defined as the ratio of force to normal velocity, F/v_n. The term z_{ac} depends on the electric coupling conditions. Suppose a load impedance Z_L is connected to the electric terminals so that, from equation (3), $E = -Z_L I$. Substituting (3) in the basic equations (1) and (2), we obtain

$$F = z_0 v_n + kI \tag{11}$$

and

$$-Z_L I = k' v_n + Z_b I. \tag{12}$$

Solution of these equations shows that

$$z_{ac} = \frac{F}{v_n} = z_0 - \frac{kk'}{Z_L + Z_b}. \tag{13}$$

3.4 SENSITIVITIES

The various impedances associated with an electroacoustic transducer have been expressed in terms of the fundamental transducer constants and the conditions of coupling. The sensitivities of a transducer are now considered.[c] Here, two types of sensitivity are of interest: the transmitting or electroacoustic sensitivity and the receiving or acoustoelectric sensitivity. Expressions for these are obtained and a proof of the reciprocity theorem, which is basic in much of underwater sound calibration work, is given.

The transmitting sensitivity $S(\mathbf{R})$ of a transducer is defined as the ratio of the pressure developed by the transducer at the point **R**, when driven electrically, to the input current to the transducer.[d] In practice, the point **R** is taken as a point at unit distance (1 meter) on the axis of symmetry of the transducer. The value of the sensitivity $S(\mathbf{R})$ depends upon the properties of both the transducer and the medium in which it is operating.

It is now necessary to express the pressure $p(\mathbf{R})$ at any point **R** in the medium in terms of the normal velocity v_n of the diaphragm. This relationship can be shown to be

$$p(\mathbf{R}) = -\frac{j\omega\rho}{4\pi} v_n \int_{S_d} G(\mathbf{R}, \mathbf{r})\, dr = -\frac{j\omega\rho}{4\pi} v_n\, g(\mathbf{R}). \tag{14}$$

Here the integral is taken over the acoustically active portion of the transducer surface, the diaphragm S_d; ρ is the density of the medium; ω is the angular frequency of the sound wave (2π times the frequency); and $G(\mathbf{R}, \mathbf{r})$ is the so-called Green's function.[e] Physically, it may be defined as the pressure which would be produced at the point **R** as a result of a point source of unit strength placed at the point **R′**, if the diaphragm of the transducer did not move. $G(\mathbf{R}, \mathbf{r})$ is simply $G(\mathbf{R}, \mathbf{R}')$ for **R′** taken at the point **r** on the closed transducer surface S. It can be shown that such a function can in principle be calculated for all ordinary surfaces S, and that it is symmetric in its arguments, that is, $G(\mathbf{R}, \mathbf{r}) = G(\mathbf{r}, \mathbf{R})$. The function $g(\mathbf{R})$ is introduced simply as an abbreviation for the integral

$$g(\mathbf{R}) = \int_{S_d} G(\mathbf{R}, \mathbf{r})\, dr. \tag{15}$$

Since we are considering the transmitting sensitiv-

[c] The transmitting and receiving sensitivities defined here bear a close relationship to the transmitting and receiving responses defined below. (See Chapter 4.)

[d] For simplicity we shall denote a point in the medium by its position vector **R** from an arbitrary origin rather than by its coordinates.

[e] Green's function, $G(\mathbf{R}, \mathbf{R}')$, is defined mathematically as a solution of the wave equation, which has a pole of residue unity at the point $\mathbf{R} = \mathbf{R}'$, which satisfies the boundary condition $\partial G(\mathbf{R}, \mathbf{R}')/\partial n = 0$ on the closed transducer surface S, and which, as $|\mathbf{R} - \mathbf{R}'| \to \infty$, behaves like

$$f\left(\frac{\mathbf{R} - \mathbf{R}'}{|\mathbf{R} - \mathbf{R}'|}\right)\frac{e^{-j\frac{2\pi}{\lambda}|\mathbf{R} - \mathbf{R}'|}}{|\mathbf{R} - \mathbf{R}'|}$$

(λ = wave length; $f\left(\frac{\mathbf{R} - \mathbf{R}'}{|\mathbf{R} - \mathbf{R}'|}\right)$ is a function whose nature is determined by the surface S), that is, it resembles an outward travelling wave. Green's function can be shown to exist mathematically for all ordinary surfaces S. It can also be shown that in the particular case of a piston-like diaphragm in an infinite rigid baffle, $G(\mathbf{R}, \mathbf{R}') = \dfrac{2\, e^{-j\frac{2\pi}{\lambda}|\mathbf{R} - \mathbf{R}'|}}{|\mathbf{R} - \mathbf{R}'|}$, when $\mathbf{R}' = \mathbf{r}$ lies on the surface of the piston or baffle.

ity, equation (6) applies and $F = -z_r v_n$. Solving for v_n from equations (6) and (1), and substituting the result into equation (14), the transmitting sensitivity is obtained as

$$S(\mathbf{R}) = \frac{p(\mathbf{R})}{I} = \frac{j\omega\rho}{4\pi}\cdot\frac{k}{z_0+z_r}g(\mathbf{R}). \qquad (16)$$

Thus the transmitting sensitivity depends on the frequency $f = \omega/2\pi$, the density of the medium ρ, the open-circuit mechanical impedance z_0, the electroacoustic coupling constant k, and the radiation impedance z_r, as well as the integral of Green's function over the surface of the transducer.

Consider next the receiving sensitivity M. Suppose that in the absence of the transducer from the medium there is present a sound field $p_{\text{inc}}(\mathbf{R})$, whose value at the position of the acoustic center of the transducer $\mathbf{R}_0$ (when the latter is not present in the medium) is $p_{\text{inc}}(\mathbf{R}_0)$.[f] Then the ratio of the open-circuit voltage generated by the transducer when in the medium to $p_{\text{inc}}(\mathbf{R}_0)$ is defined as the receiving sensitivity M.[g]

The value of M depends upon the type of wave, that is, p_{inc}. For practical applications, the important case is that for which p_{inc} is a spherical wave with center at some point $\mathbf{R}_c$. The plane wave sensitivity can be considered to be the sensitivity to spherical waves when $\mathbf{R}_c$ is infinitely distant from $\mathbf{R}_0$. In this case p_{inc} can be written as

$$p_{\text{inc}}(\mathbf{R}) = \Phi\frac{e^{-j\frac{2\pi}{\lambda}|\mathbf{R}-\mathbf{R}_c|}}{|\mathbf{R}-\mathbf{R}_c|}. \qquad (17)$$

The actual pressure present at a point $\mathbf{R}$ when the transducer is in the medium must now be found. If the transducer diaphragm did not move, the pressure, from the definition of Green's function, would be

$$\Phi G(\mathbf{R}, \mathbf{R}_c).$$

On the other hand, if no incident sound pressure p_{inc} is present in the medium but the transducer surface has a velocity v_n, the pressure at a point $\mathbf{R}$ in the medium is as given by equation (14). If these two pressures are added, the actual pressure at $\mathbf{R}$, $p(\mathbf{R})$, when p_{inc} is present, is obtained and the transducer diaphragm has a velocity v_n. Thus

$$p(\mathbf{R}) = \Phi G(\mathbf{R}, \mathbf{R}_c) - \frac{j\omega\rho}{4\pi}v_n\int_{S_d} G(\mathbf{R}, \mathbf{r})\,d\mathbf{r} \qquad (18)$$

$$= \Phi G(\mathbf{R}, \mathbf{R}_c) - \frac{j\omega\rho}{4\pi}v_n\,g(\mathbf{R}).$$

Since the total force on the transducer diaphragm is the integral over the diaphragm of the pressure at each point on its surface, then

$$F = \int_{S_d} p(\mathbf{r})\,d\mathbf{r} = \Phi\int_{S_d} G(\mathbf{r}, \mathbf{R}_c)\,d\mathbf{r} - \frac{j\omega\rho}{4\pi}v_n\int_{S_d} g(\mathbf{r})\,d\mathbf{r}. \qquad (19)$$

Since $G(\mathbf{r}, \mathbf{R}_c) = G(\mathbf{R}_c, \mathbf{r})$ from the symmetry of Green's function, the first term can be written as $\Phi g(\mathbf{R}_c)$. If we compare equation (19) with equation (5), we see that

$$F_0 = \Phi g(\mathbf{R}_c) \qquad (20)$$

and

$$z_r = \frac{j\omega\rho}{4\pi}\int_{S_d} g(\mathbf{r})\,d\mathbf{r} = \frac{j\omega\rho}{4\pi}\iint_{S_d} G(\mathbf{r}, \mathbf{r}')\,d\mathbf{r}'\,d\mathbf{r}. \qquad (21)$$

These quantities may be computed when Green's function for the surface S is known.[h]

If (5) is substituted for F, with F_0 and z_r given by equations (20) and (21), in the fundamental equations (1) and (2) and the case where the transducer is

[f] The acoustic center is the center of symmetry if it exists, but for this discussion it may be any arbitrarily chosen point on the transducer. The incident sound field pressure p_{inc} satisfies the wave equation $\left[\nabla^2 + \left(\frac{2\pi}{\lambda}\right)^2\right] p_{\text{inc}}(\mathbf{R}) = 0$, where λ is the wave length and ∇^2 is the Laplacian operator.

[g] In practice the receiving response is always given for a uniform plane wave normally incident on the transducer.

[h] It can further be shown that, for an arbitrary incident sound field p_{inc}, one has

$$p(\mathbf{R}) = p_{\text{inc}}(\mathbf{R}) - \frac{1}{4\pi}\int_{S_d}\frac{\partial p_{\text{inc}}(\mathbf{r})}{\partial n}G(\mathbf{R}, \mathbf{r})\,d\mathbf{r} - \frac{j\omega\rho}{4\pi}v_n\int_{S_d} G(\mathbf{R}, \mathbf{r})\,d\mathbf{r}.$$

The first two terms reduce to $\Phi\,G(\mathbf{R}, \mathbf{R}_c)$ as shown in equation (18), if p_{inc} is the spherical wave of equation (17). If $p(\mathbf{R})$ is integrated over the surface S_d, the integral of the first term p_{inc} is what F_{inc} was called, while the integral of the second term is what $F_{\text{rigid diff}}$ was called. The last term is again $-z_r v_n$.

electrically terminated in a load impedance Z_L is considered, so that $E = -Z_L I$, v_n can be eliminated between the equations and the following is obtained for the voltage output of the transducer:

$$E = -Z_L I = \frac{Z_L}{Z_L + Z_b - \dfrac{kk'}{z_0 + z_r}} \cdot \frac{k'}{z_0 + z_r} F_0. \tag{22}$$

We are interested in the open-circuit voltage E_{oc}. This is obtained from equation (22) by letting $Z_L \to \infty$; thus

$$E_{oc} = \frac{k' F_0}{z_0 + z_r}. \tag{23}$$

Since

$$p_{\text{inc}}(\mathbf{R}_0) = \Phi \frac{e^{-j\frac{2\pi}{\lambda}|\mathbf{R}_0 - \mathbf{R}_c|}}{|\mathbf{R}_0 - \mathbf{R}_c|}, \tag{24}$$

the receiving sensitivity, using equation (20) for F_0, is

$$M = \frac{E_{oc}}{p_{\text{inc}}(\mathbf{R}_0)} = \frac{k' g(\mathbf{R}_c)\,|\mathbf{R}_0 - \mathbf{R}_c|}{(z_0 + z_r)\, e^{-j\frac{2\pi}{\lambda}|\mathbf{R}_0 - \mathbf{R}_c|}}. \tag{25}$$

3.5 PROOF OF RECIPROCITY THEOREM

The reciprocity theorem will now be proved. This theorem applies to all transducers which obey the condition

$$|k| = |k'|, \tag{26}$$

that is, equality of the absolute values of the electroacoustic and acoustoelectric coupling constants. It is simple to show that this condition is satisfied for the various idealized transducers[i] considered in Chapter 2. The statement of the theorem is as follows: The absolute value of the ratio of the receiving sensitivity M due to a point source of spherical sound waves[j] at $\mathbf{R}$, at a distance d from the acoustic center of the transducer to the transmitting sensitivity S, measured at the point $\mathbf{R}$, is a constant independent of all particular characteristics of the transducer. The value of the constant is: $|M/S| = 2d\lambda/\rho c$, where λ and c are the wave length and velocity of sound, respectively, and ρ is the density of the medium. The applications of this theorem are discussed in Chapters 4 to 7.

The theorem is readily proved by taking the ratio of M as given by equation (25) with $\mathbf{R}_c = \mathbf{R}$, and S as given by equation (16):

$$\frac{M}{S} = \frac{\dfrac{k' g(\mathbf{R})\, d}{z_0 + z_r} e^{j\frac{2\pi}{\lambda}d}}{\dfrac{4\pi}{j\omega\rho} \cdot \dfrac{k}{z_0 + z_r} \cdot g(\mathbf{R})} = \frac{4\pi d}{j\omega\rho}\left(\frac{k'}{k}\right) e^{j\frac{2\pi}{\lambda}d}. \tag{27}$$

Taking the absolute value of this equation, and remembering that $|k'| = |k|$, we obtain

$$\left|\frac{M}{S}\right| = \frac{4\pi d}{\rho\omega} = \frac{2d\lambda}{\rho c}. \tag{28}$$

The reciprocity theorem, proved here for the case of a rigidly vibrating diaphragm, can be shown to hold for any general mode of diaphragm vibration where $v_n(r)$ is a function of position on the diaphragm.[k]

3.6 EFFICIENCIES

Having discussed the sensitivities of a transducer and their relationship through the reciprocity theorem, a treatment of efficiencies follows, beginning with the efficiency of the transducer on transmission, the projector efficiency. This is defined as the ratio of the total acoustic power output of the transducer to the electric power input. Several expressions for the projector efficiency E_p will be derived which will be useful for different purposes.

The acoustic power output may be shown to be[74,75]

$$\frac{1}{2}\left[\int_\Sigma p(\mathbf{R})\, v_n^*(\mathbf{R})\, d\Sigma + \int_\Sigma p(\mathbf{R})^*\, v_n(\mathbf{R})\, d\Sigma\right], \tag{29}$$

[i] Thus, for the case of the electrodynamic moving ribbon pressure-gradient transducer (see Chapter 2) $k = -Bl$, $k' = Bl$, where B is the magnetic flux density in the region where the ribbon moves, and l is the effective length of the ribbon. Values of k and k' for other types of transducers are given in the literature.[80, 81]

[j] This restriction is not necessary. It may be shown that the reciprocity theorem is valid for any source distribution for the incident waves just so long as the distance between sources and transducer is large compared to the dimensions of either of them.

[k] Another extension of the theorem is to the case of a series of transducers individually obeying reciprocity and coupled by electric and mechanical transformers. Then the condition $|k'| = |k|$ will hold for the coupling between the input E, I and output F, v_n, if it holds for the individual transducers, and the reciprocity theorem will be valid for the series considered as a unit.

the asterisk denoting the complex conjugate and Σ being any closed surface containing the transducer. The electric power input is given by $|I|^2 R_{el}$ where $|I|$ is the absolute value of the (complex) current and R_{el} is the real part of the effective electric impedance of the transducer Z_{el}.

If Σ is chosen as a large sphere of radius d centered at the transducer, we have $v_n = p/\rho c$ on S.[74,75] Then the expression for the acoustic power output becomes:

$$\frac{1}{\rho c}\int_{\Sigma} |p|^2 \, d\Sigma = \int_{\Sigma} I \, d\Sigma,$$

$d\Sigma$ being now an element of area on the sphere and I the sound intensity. Introducing the directivity factor δ, defined as[l]

$$\delta = \frac{\displaystyle\int_{\Sigma}\left(\frac{|p|^2}{\rho c}\right) d\Sigma}{\left(\dfrac{|p|^2_{\text{axis}}}{\rho c}\right) 4\pi d^2} = \frac{I_{\text{aver}}}{I_{\text{axis}}}, \tag{30}$$

with p_{axis} the pressure at distance d on the axis of symmetry of the transducer, or, generally, on any fixed axis, one obtains for the projector efficiency

$$E_p = \frac{\dfrac{4\pi d^2\, \delta |p|^2_{\text{axis}}}{\rho c}}{|I|^2 R_{el}} = \frac{4\pi d^2\, \delta |S|^2}{\rho c\, R_{el}} = \frac{4\pi\delta}{\lambda^2} M^2 \frac{\rho c}{4R_{el}}, \tag{31}$$

where S and M are the transmitting and receiving sensitivities; see equations (16), (25), and (28).

Another possible choice for Σ is the surface S of the transducer. Then, v_n is the normal velocity of the transducer surface, assumed constant over the diaphragm. Thus from equations (6) and (29) we have the projector efficiency expressed as

$$E_p = \frac{|v_n|^2 r_r}{|I|^2 R_{el}} \tag{32}$$

where r_r is the real part of the radiation impedance z_r.

Finally, using equations (7) and (8) to find v_n/I and equation (9) from R_{el} and substituting the results into equation (32), we obtain

$$E_p = \frac{r_r}{\text{Re}\left(Z_b - \dfrac{kk'}{z_0 + z_r}\right)} \frac{|k|^2}{|z_0 + z_r|^2} \tag{33}$$

where $R_{el} = \text{Re}\left(Z_b - \dfrac{kk'}{z_0 + z_r}\right)$ is the real part of the effective electric impedance, Z_{el}. It may be shown[39] that a sufficient condition for E_p to be 100 per cent is $R_b = r_0 = 0$, that is, the blocked electric and open-circuit mechanical impedances have no real parts.

It is worth pointing out in connection with equation (33) that the projector efficiency (at resonance) of a resonant transducer may be determined by purely electrical methods. (See reference 39.) In a resonant transducer, the response as a function of frequency has a sharp maximum when the impressed frequency coincides with a natural frequency of the transducer itself. If one measures the electric impedance of the transducer at a frequency well above and below its resonant frequency, the result will be essentially Z_b, the blocked impedance.[m] Suppose now one measures the electric impedance of the transducer at resonance in air. Then z_r is approximately zero and the motional impedance (the difference between the measured electric impedance and Z_b) will be $-kk'/z_0$. Next one measures the impedance at resonance in water. Then the motional impedance in water $-kk'/(z_0 + z_r)$ is known. These three measurements suffice for the determination of E_p, if the transducer obeys the reciprocity condition $|k| = |k'|$, so that $|k|^2 = |kk'|$.

This may be seen as follows: At resonance the imaginary part of $z_0 + z_r$ vanishes,[n] and $|z_0 + z_r|^2 = (r_0 + r_r)^2$. Then equation (33) may be written as

$$E_p = \frac{r_r}{R_{el}} \frac{|k|^2}{(r_0 + r_r)^2} = \frac{R_{el}(r_0 + r_r)}{|kk'|}\left[1 - \frac{\dfrac{|kk'|}{r_0 + r_r}}{\dfrac{|kk'|}{r_0}}\right], \tag{34}$$

where the second form uses the reciprocity condition: $|k|^2 = |kk'|$.

It is now seen that R_{el}, $\dfrac{|kk'|}{r_0 + r_r}$, and $\dfrac{|kk'|}{r_0}$ are the only quantities needed for a knowledge of E_p at resonance. All of these can be found by the method described, assuming that r_0 is a slowly varying function of frequency so that r_0, at the resonance frequency in air, is close in value to r_0 at the resonance frequency in water.

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l For further discussion of the directivity factor δ and of the directivity index $\equiv 10 \log \delta$, see Chapter 4.

m Z_b is in general a function of frequency but does not show resonance properties. Hence its value at the resonant frequency of the transducer may be found by joining the portions of the curve found above and below resonance by a smooth curve.

n When the imaginary part of $z_0 + z_r$ vanishes, the responses S and M have their maximum values; see equations (16) and (25).

3.7 MAXIMUM ELECTRIC POWER OUTPUT ON RECEPTION AND THRESHOLD PRESSURE

Maximum electric power P_{max} is transferred to a receiver when the electric load impedance of the receiver is the complex conjugate of the effective electric impedance of the transducer. Under this condition, by Thévenin's theorem

$$P_{max} = \frac{E_s^2}{R_{el}} = \frac{E_{s(oc)}^2}{4R_{el}} \tag{35}$$

$$= \frac{|p_{inc}|^2 M^2}{4R_{el}} = \frac{|p_{inc}|^2}{\rho c}\frac{\lambda^2}{4\pi\delta}E_p,$$

where E_s is the signal voltage across the load in the matched circuit, $E_{s(oc)}$ is the signal voltage that would be developed by the transducer on open circuit, M is the receiving sensitivity, and E_p is the projector efficiency. The last form of equation (35) follows from the last form of equation (31). Equation (35) suggests that the quantity $\frac{\lambda^2}{4\pi\delta}$, which has the dimensions of an area and is usually called the effective area, has the significance of being the maximum cross section for energy absorption by the transducer from the sound field. This follows from the fact that $\frac{|p^2_{inc}|}{\rho c}$ is the incident intensity of sound, E_p never exceeds unity, and maximum power is absorbed in a matched circuit.

An important parameter of the transducer is its threshold pressure p_t. This is defined as the pressure in a uniform, plane-wave, free sound field propagated parallel to the acoustic axis of the transducer, which produces a signal power output in the load equal to the inherent thermal noise power in the load. (See Chapter 4 for a full discussion.) The noise power is taken in a 1-cycle band and the transducer is supposed to be in a matched circuit. The noise power in the load in a matched circuit is one-half of the open-circuit noise power in the transducer (since noise pressures add in random phase). This open-circuit noise power in a 1-cycle band is given by $4KT$ where K is Boltzmann's constant and T is the absolute temperature of the device.[70] Consequently, the threshold pressure is given by the relation

$$\frac{|p_t|^2}{\rho c}\frac{\lambda^2}{4\pi\delta}E_p = \frac{1}{2}(4KT). \tag{36}$$

3.8 GENERALIZATION OF THEORY TO ANY TYPE OF DIAPHRAGM MOTION

The treatment of the theory of electroacoustic transducers given above for transducers in which the diaphragm velocity is the same at all points can readily be generalized to the case where there is no such restriction on the velocity distribution. The form that the generalization takes follows in outline. The fundamental equations for the transducer can be written as

$$p(\mathbf{r}) = \int_S z_0(\mathbf{r},\mathbf{r}')\, v_n(\mathbf{r}')\, d\mathbf{r}' + k(\mathbf{r})\, I \tag{37}$$

and

$$E = \int_S k'(\mathbf{r}')\, v_n(\mathbf{r}')\, d\mathbf{r}' + Z_b\, I. \tag{38}$$

Here r and r' are points on the transducer surface S; $p(\mathbf{r})$ and $v_n(\mathbf{r})$ are the pressure and normal velocity at the point r, respectively. The functions $z_0(\mathbf{r},\mathbf{r}')$, $k(\mathbf{r})$, and $k'(\mathbf{r}')$ are functions characteristic of the transducer which are the generalizations of z_0, k, and k' in the simpler treatment given earlier. For coupling to an electric source of generated voltage E_0 and internal impedance Z_{int}, the equation

$$E = E_0 - Z_{int}\, I \tag{4}$$

again holds. However, for coupling on the acoustic side we now have

$$p(\mathbf{R}) = p_0(\mathbf{R}) - \int_S z_r(\mathbf{R},\mathbf{r}')\, v_n(\mathbf{r}')\, d\mathbf{r}' \tag{39}$$

where

$$p_0(\mathbf{R}) = p_{inc}(\mathbf{R}) - \frac{1}{4\pi}\int_S \frac{\partial p_{inc}(\mathbf{r}')}{\partial n} G(\mathbf{R},\mathbf{r}')\, d\mathbf{r}' \tag{40}$$

and

$$z_r(\mathbf{r},\mathbf{r}') = \frac{j\omega\rho}{4\pi} G(\mathbf{r},\mathbf{r}') \tag{41}$$

and $\mathbf{R}$ is any point in the medium. ($\mathbf{R}$ may be taken equal to r.) Here $G(\mathbf{r},\mathbf{r}')$ is the same Green's function introduced earlier. The quantity $z_r(\mathbf{r},\mathbf{r}')$ is an acoustic radiation impedance continuous matrix which is the

generalization of the previously used radiation impedance z_r. When no sources other than the transducer are present in the medium, the pressure at any point **R** in the medium is, by equations (39) and (40), given as

$$p(\mathbf{R}) = -\frac{j\omega\rho}{4\pi}\int_S G(\mathbf{R}, \mathbf{r}')\, v_n(\mathbf{r}')\, d\mathbf{r}'. \tag{42}$$

The above equations allow the behavior of the transducer to be calculated under any conditions. The various impedances, sensitivities, and efficiencies can be found in a manner analogous to that used above. These calculations involve, in general, the solution of linear integral equations which can be solved in principle, though practical solutions may be difficult to obtain except in simple cases. The reciprocity theorem, equation (28), can be proved in this general case provided that

$$|k(\mathbf{r})| = |k'(\mathbf{r})| \tag{43}$$

and

$$z_0(\mathbf{r},\mathbf{r}') = z_0(\mathbf{r}',\mathbf{r}). \tag{44}$$

Chapter 4

TYPES OF ACOUSTIC MEASUREMENTS

By *Eginhard Dietze*

The choice of what should be measured is probably as important a part of a testing program as any and requires a clear understanding of the nature and purposes of the tests and of the character and applications of the device under test. Furthermore, the conditions under which the tests are made must be carefully controlled. The existence of controlled conditions is one of the principal reasons for substituting laboratory tests for field tests.

The tester, furthermore, in order to carry out his task intelligently, must possess a broad knowledge of the applications of the device as well as of measurement technique. Assume, for instance, that an echo-ranging projector is to be tested. To set up a program for such tests, it is necessary to know what factors are important in echo ranging and how these factors depend on the physical characteristics of the device. Only then can tests be made that will throw light on how the device will perform in service and how its performance could be improved.

A great deal of thought has been given by the Underwater Sound Reference Laboratories [USRL] to these questions. Based on these studies, the pertinent physical characteristics that should be measured in a calibration test on an echo-ranging projector are (1) directivity (directivity index, horizontal and vertical beam widths, magnitude of largest side lobes), (2) frequency-response characteristic, (3) power output (efficiency), (4) selectivity, (5) threshold pressure, (6) receiving response, and (7) impedance.

It is necessary to devise proper tests for the precise measurement of these characteristics. In acoustic tests, this is not always simple, and even with the greatest care it is usually not possible to equal the precision of electric circuit tests. All factors should be of the optimum design in order to achieve even a reasonable degree of precision. A first requirement in this connection is one of testing equipment. Any effort expended in obtaining the best possible laboratory equipment will be well repaid. It is almost axiomatic that without such equipment the situation is hopeless. Assuming that such equipment is available, there are certain fundamental rules of testing which must be observed. The most important one, although very simple, is frequently violated, often with disastrous results. This rule is as follows: *In a test, as in any experiment, only one factor may be varied at a time. All other factors must be held constant throughout the tests.* Usually more than one characteristic is to be measured, so that more than one test must be made. The above rule, that all factors except the one under test must be kept constant, applies to the entire testing program. A few illustrations which apply to underwater sound testing follow.

It is essential that all characteristics of the medium remain constant throughout the tests. For example, temperature: unless it is a variable of the test, the temperature must be uniform throughout the program. In addition, the device itself must be in temperature equilibrium with the medium. Depending on its size and type of construction, this may require waiting several hours or even a full day, while the unit is immersed, before tests can be started. It has also been found that results obtained at one temperature do not necessarily apply at other temperatures. Thus the temperature of the water during the tests, the temperature dependence of the device, and the speed with which it reaches temperature equilibrium are important factors.

In any extended testing program, special care must be taken that the signal levels, the transmission properties of the medium, and the noise background do not change. Drifts in the amplifier or in the oscillator characteristics affect the acoustic conditions by changing the level or the frequency of the sound in the water. To avoid such drifts, it is necessary to check the electric system frequently during the tests. Similar precautions must be observed in using acoustic devices. For instance, x-cut Rochelle salt crystals are variable under some conditions and for this reason are undesirable as standards. In many devices one side is grounded, increasing the chance for noise pickup and necessitating proper shielding of the leads.

Another factor to be considered is that all measurements must be made at the same point in the circuit, that is, the leads should be the same for all tests. The

same auxiliary equipment, such as tuning coil or condenser and polarizer, should also be used throughout the testing program. For example, in the measurement of electric power, the current and impedance, or current, voltage, and phase angle must be measured from the same set of terminals. In more complicated tests the matter of measuring from a single pair of terminals, however, is sometimes overlooked. For instance, in order to determine the efficiency of a projector, the transmitting response must be obtained, the directivity measured, and the impedance of the projector and of the source determined. To obtain the correct answer, all electric measurements that enter into these tests must be made from the same terminals. Frequently this is inconvenient. The driving amplifier, for instance, is at one place in the laboratory, while the impedance bridge is at another. If an extra lead is added in either connection, an error results.

It may be noted in passing that the efficiency thus determined includes any losses in the system beyond the point where the measurements are made. If the efficiency of the projector exclusive of these losses is desired, the measurements must be made directly at its terminals or the losses must be eliminated from the data by computation. The latter method is usually more time-consuming and less accurate.

A general principle of testing is that it is easier to make relative measurements than absolute measurements, and that the precision of relative tests, for the same amount of effort, is much greater. The easiest tests to make are the so-called *A-B comparisons* which involve immediate switching between two conditions. Usually one of the conditions, say A, which is well-known, serves as the reference condition, and the other, B, which includes the unknown, is the test condition. Many a testing difficulty can be avoided by reducing the program to a number of such comparison tests, and, if at all possible, tests should always be set up on that basis.

With these principles in mind, many specific practices have been established by USRL. Some of these are described in Section 6.1.4. The rest of this section is concerned with the physical characteristics to be measured in calibration tests on underwater sound equipment.

Most acoustic devices are reversible, that is, they can do two things depending on how they are used: (1) When an electric voltage is applied at their terminals, they generate acoustic power, and (2) when acoustic power is supplied to them, they generate an electric voltage. A device which has these properties in the underwater sound field is called a transducer. The first action is called transmitting and the second receiving. Certain conventions[a] have been set up by agreement among the different groups interested in the underwater sound field for the measurement of transmitting and receiving performance. These conventions are of value in making the meaning of measurement results precise to all people in the group. Also, by expressing all results on the same basis, different measurements can be more easily compared. The most important use of test data is usually to determine which instrument is best from among a number that are available for a particular application.

4.1 TRANSMITTING

Transmitting measurements usually involve three factors: (1) the acoustic pressure delivered by the device in the desired direction for a known electric input, (2) the distribution of the acoustic pressure in other directions, and (3) the variation of the pressure with frequency.

It is noted that these items correspond respectively to (3), (1), and (2) at the beginning of this chapter.

These quantities must be expressed in such a way that their meaning is unambiguous and that they afford a ready means of comparing different designs. For example, a statement of the pressure delivered does not of itself tell much about the performance of a device, since it is possible to change the pressure by increasing or decreasing the electric input. Consequently, the electric supply conditions must be specified as well.

In most practical cases the projector is fed from an amplifier. The most definite way to tie down the electrical system in a practical way, therefore, is to specify the amplifier. For calibration purposes it is desirable that a class A amplifier be used, because the performance of such an amplifier can be accurately specified and controlled. From the standpoint of circuit analysis, a class A amplifier can be replaced by a generated voltage e_g and an internal resistance r_g. The same analysis also applies to class B and C amplifiers, but the values then are a function of the power delivered, whereas in the case of the class A amplifier these

[a] Conference on underwater sound projectors in the Office of the Coordinator of Research and Development of the Navy, July 19, 1944.

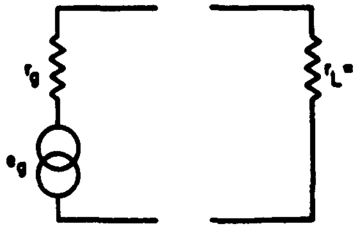

FIGURE 1. Circuit referred to by equation (1).

values are independent of this factor up to the point where overloading sets in.

It is seen from the above that the power delivered by an amplifier is a function of the load impedance. For this reason, the use of a fixed input power, a fixed applied voltage or a fixed applied current in determining the variation with frequency of the pressure delivered by a projector (the impedance of which changes with frequency) in general does not provide a response characteristic that is representative of actual service conditions. This consideration has led to the use of *available power* as a basis.

4.1.1 Available Power

Available power[47] is defined as the power which a driver having a fixed generated voltage e_g and a fixed internal resistance r_g delivers into a matched load resistance r_L. Figure 1 illustrates the circuit.

From this circuit it can be seen that the power delivered into the load resistance $r_L = r_g$ is

$$P_A = \left(\frac{e_g}{r_g + r_L}\right)^2 r_L = \frac{e_g^2}{4r_g}. \tag{1}$$

The actual input power delivered into a projector of impedance $z = r + jx = |z|\cos\theta + j|z|\sin\theta$ has the following value:

$$P_I = \left|\frac{e_g}{r_g + z}\right|^2 r = P_A \frac{4rr_g}{(r_g + r)^2 + x^2}.$$

Hence,

$$10 \log \frac{P_I}{P_A} = 10 \log \left[\frac{4rr_g}{(r_g + r)^2 + x^2}\right]. \tag{2}$$

The term $10 \log P_I/P_A$ is well-known in transmission circuit theory[69] and is the *transition loss* between the resistance r_g and the impedance z. On Figure 2 curves of this transition loss are plotted against the ratio of the impedance magnitudes r_g/z for different phase angles θ.

If a projector is tuned, so that at resonance its impedance is a pure resistance, the maximum power will then be delivered by the driver to the projector if this resistance matches the internal resistance of the driver, that is, when $r_L = r_g$. It is seen that under these conditions, the actual power P_I equals the available power P_A. In all other cases the actual power is less than the available power. The efficiency of the electric system under these conditions, however, is only 50 per cent, since the amount of power dissipated in the output tubes equals that supplied to the load. In practical designs using class B or C amplifiers, it is an advantage to use a lower source impedance, about ¼ r_L. This improves the electric circuit efficiency and reduces the power dissipation in the output tubes, thus permitting smaller tubes to be employed. In testing, the source impedance of the actual system should be simulated.

4.1.2 Transmitting Response

The transmitting response of a projector of given impedance is expressed in terms of the pressure at 1 meter distance on the acoustic axis in decibels versus reference pressure (1 dyne per sq cm) per watt available power from a given generator impedance (assumed to be purely resistive).

In connection with this definition of transmitting response, it should be noted that the pressure delivered increases as the square root of the available

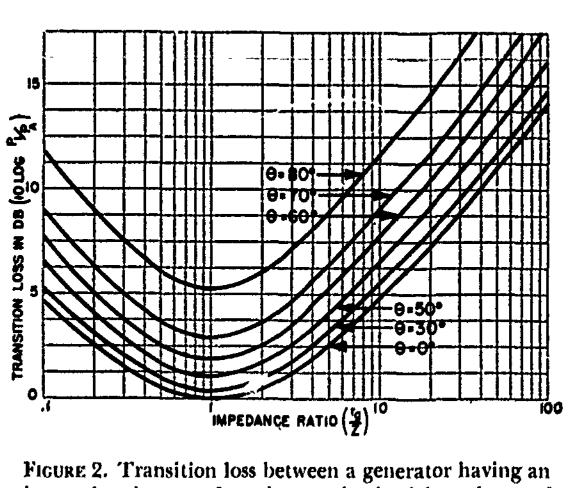

FIGURE 2. Transition loss between a generator having an internal resistance of r_g ohms and a load impedance of magnitude z and phase angle θ.

power. Thus, formulating the mathematical expression for the response,

$$R_T = 20 \log \frac{p}{\sqrt{P_A}} = 20 \log p - 10 \log P_A. \quad (3)$$

In equation (3), 20 log p gives the pressure in decibels versus 1 dyne per sq cm (1 dyne per sq cm is called *reference pressure*) and 10 log P_A is the power level referred to 1 watt. For actual testing, the practice of expressing power levels in decibels versus 10^{-16} watt has developed.

It will be noted that 1 meter is chosen for the reference distance. This, of course, does not mean that all calibrations are to be made at that distance. The actual testing distance will depend on considerations of obtaining waves which are sufficiently plane so that spherical wave corrections will not be required either for the projector under test or for the receiving hydrophone, that is, the testing distance will depend on the size of the instruments and the frequency. Otherwise, the testing distance will be made as short as possible to minimize interference from reflections, etc. The *testing distance* d will be stated in connection with all tests and the correction C in decibels to d_0 = 1 meter will be made on the basis of spherical waves; thus

$$C = 20 \log \frac{d}{d_0}. \quad (4)$$

A similar consideration applies with respect to the power to be used in the tests. While the response is referred to 1 watt, it would obviously be incorrect to make all tests at that power level. If the device is linear, the testing power used is of no consequence, but if the response varies with power level, then the tests should be made at the actual working levels used in service and the testing power should be stated. A load characteristic should be furnished showing the relation between acoustic power output (or pressure on the axis) and available power.

4.1.3 Directivity

The next item to be measured concerns the distribution of the acoustic pressure with direction. This is measured by determining the pressure over a spherical surface having the projector as the center, the pressure p in any one direction being expressed in

FIGURE 3. Three-dimensional directivity pattern for a circular plate. Frequency = 25 kc, diameter of plate = 15 in. Decibel values shown give response relative to that on normal axis.

decibels versus the pressure p_0 on the acoustic axis of the device. For the *acoustic axis* an axis of symmetry of the device is usually chosen, which frequently is also the direction of maximum response. A plot of these values is called a *directivity pattern*. A view of a three-dimensional directivity pattern for a circular plate is shown in Figure 3. For devices which are symmetrical, such as a circular plate, the directivity is the same in all planes containing the major axis normal to the surface. Thus the pressure distribution need be measured only in one plane, resulting in a great reduction of work. A planar directivity pattern is shown in Figure 4. This is the usual way of plotting these patterns. Devices which are not circular usually have several major axes. Patterns should then be taken in all planes containing one of these axes.

The *directivity index* is defined as the ratio in decibels of the intensity I ($I = \frac{p^2}{\rho c}$ far away from the source) averaged over all directions to the intensity I_0 on the acoustic axis of the device:

$$\Delta = 10 \log \frac{I_{av}}{I_0} = 20 \log \frac{\sqrt{(p^2)_{av}}}{p_0}. \quad (5)$$

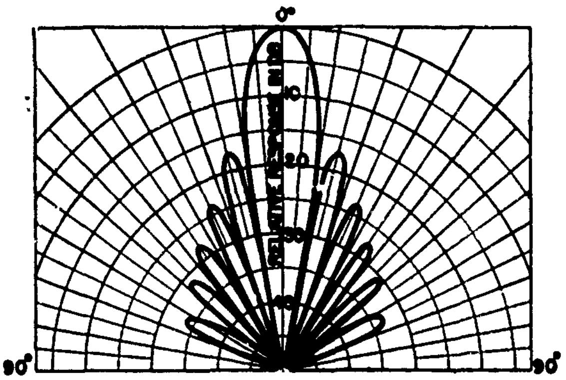

FIGURE 4. Planar directivity pattern for a circular plate. Frequency = 25 kc, diameter of plate = 15 in.

There are several cases for which a directivity index can be obtained in a relatively simple manner.[14] If the directivity pattern of the transducer has rotational symmetry about the acoustic axis, one may make use of the following formula:[38]

$$\Delta = 10 \log_{10} \left[\frac{1}{2} \int_0^{\pi} \frac{I_a}{I_0} \sin \alpha \, d \right. \qquad (6)$$

In this formula, α represents the angle from the acoustic axis, I_a the intensity at this angle, and I_0 the intensity on the axis. The above formula is valid, for example, in the case of a circular diaphragm vibrating symmetrically about this normal axis. In the case of a line source, the acoustic axis is usually taken perpendicular to the line. If the directional pattern of the line is symmetrical about the line itself, the directivity index is given by the formula:[38]

$$\Delta = 10 \log_{10} \left[\frac{1}{2} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{I_{\alpha'}}{I_0} \cos \alpha' \, d\alpha' \right], \qquad (7)$$

where α' is now the angle measured from the acoustic axis (normal to the line) in a plane including the acoustic axis and the line itself.

To indicate the use of these formulas, consider the pattern shown in Figure 4, representing a measured pattern for a circular piston in a plane including the acoustic axis. To find the directivity index for the pattern, equation (6) above is applied. The integral is evaluated graphically by means of a planimeter. This requires obtaining for different angles the ratio I_a/I_0. For instance, at 25 degrees the response is 24 db below the peak. Therefore $10 \log I_a/I_0 = -24$ or $I_a/I_0 = 0.004$. The sine of 25 degrees is 0.26. Consequently $I_a/I_0 \sin \alpha = 0.00104$. The values of $I_a/I_0 \sin \alpha$ are computed for all angles and plotted on rectilinear graph paper against the angle α expressed in radians (1 radian = 57.3 degrees). This is illustrated in Figure 5. The area under the curve is measured with a planimeter and is found to be 5 square inches. In this particular case the scales were chosen so that 1 inch on the abscissa represents 0.1 radians and 1 inch on the ordinate represents an intensity ratio $I_a/I_0 = 0.01$. Thus, 1 square inch represents a contribution to the integral of 0.001. Hence, the total area gives

$$\int_0^{\pi} \frac{I_a}{I_0} \sin \alpha \, d\alpha = 0.001 \times 5.00 = 0.005.$$

Equation (6) includes a factor of ½ in front of the integral. Thus the directivity factor is 0.0025 and the corresponding directivity index Δ is

$$\Delta = 10 \log 0.0025 = -26 \text{ db}.$$

The procedure in the case of a line is analogous to the one described above, except that $\cos \alpha$ is used in all cases in place of $\sin \alpha$, as indicated by comparison of equations (7) and (6).

Sometimes the pattern as obtained experimentally is not exactly symmetrical. In that case, it is usually sufficiently accurate to use the average values of the two halves of the pattern obtained experimentally.

This computation is quite straightforward but somewhat tedious. Figure 6 shows a chart which has been prepared to reduce the amount of algebraic computation involved. This chart shows a family of curves, each curve corresponding to a particular value of $I_a/I_0 \sin \alpha$. The chart is used in conjunction with the directivity pattern, plotted on polar coordinate paper, of the instrument whose directivity index is to be obtained. The use of the chart is as follows: The transparent chart is laid over the directivity pattern of the instrument so that the coordinate systems on the two charts coincide. Then, to find the value of $I_a/I_0 \sin \alpha$ for any angle α, one proceeds along the radial line corresponding to the angle α until one reaches the intersection of that line with the directivity pattern of the instrument. The point of intersection of the pattern and the line will then fall on

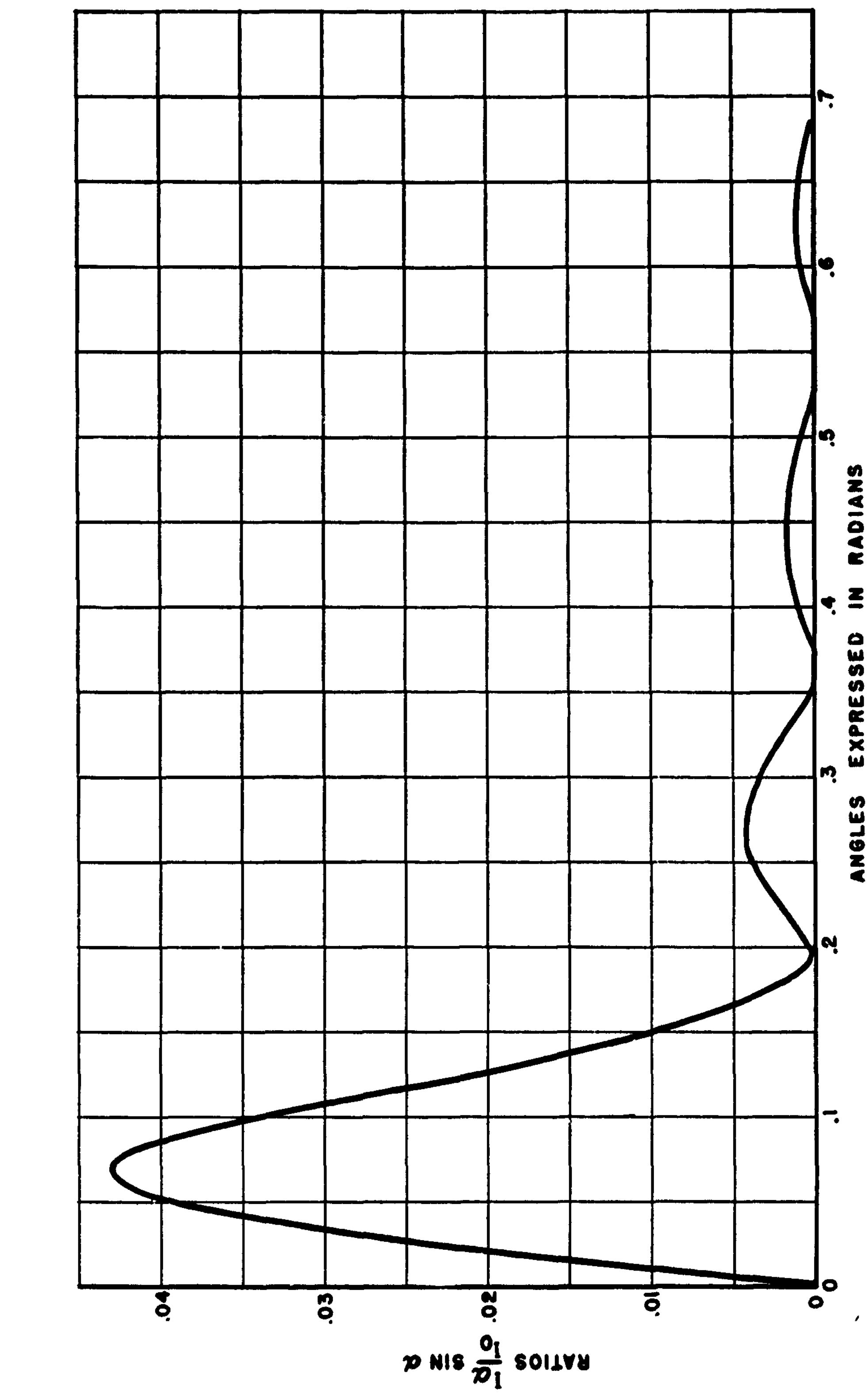

FIGURE 5. Computation of directivity index for a circular plate vibrating at uniform amplitude and in phase. Frequency = 25 kc, diameter of plate = 15 in.

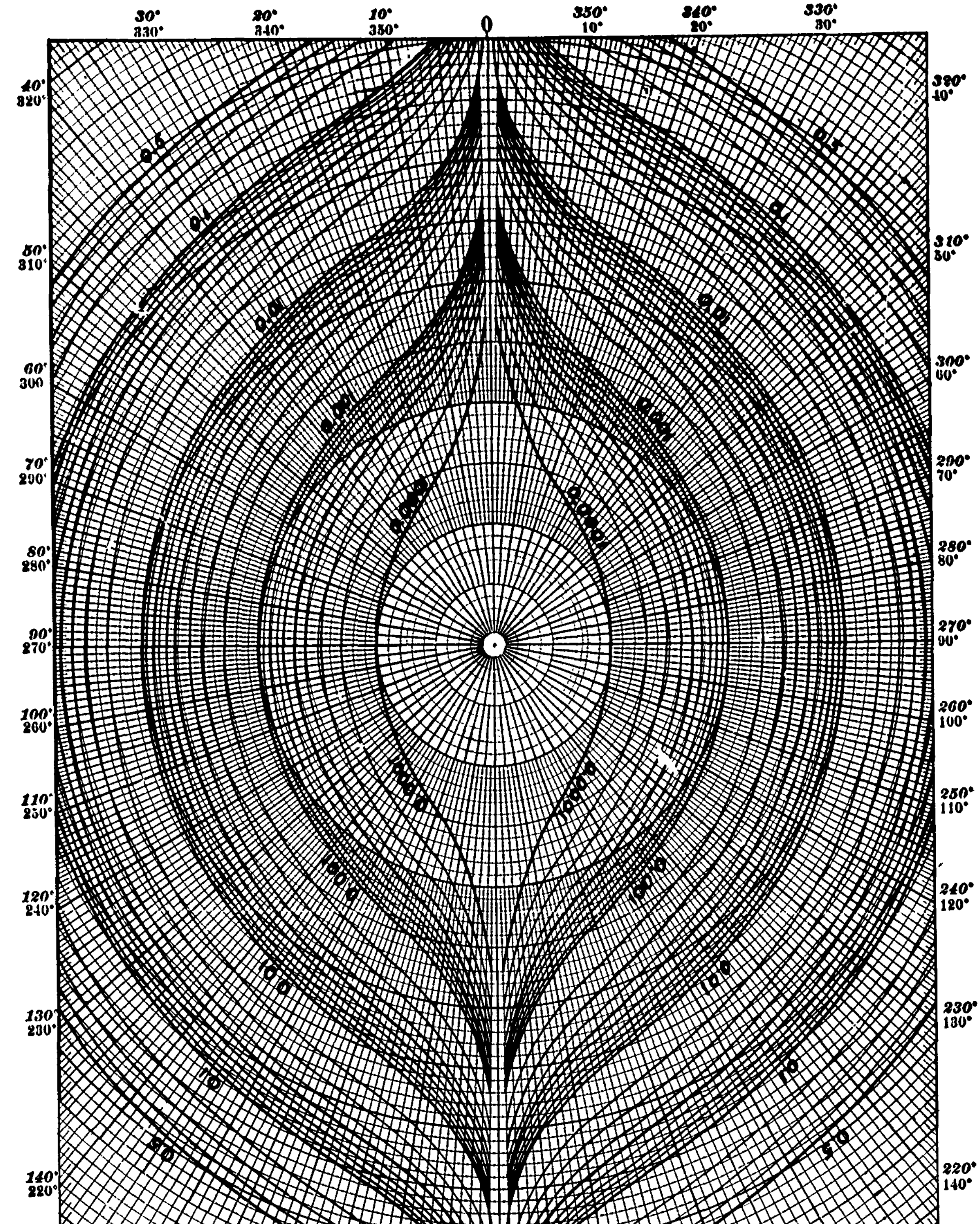

Figure 6. Directivity index calculator.

one, or between two, of the curves of the family of curves drawn on the chart. Suppose, for example, that this point falls about 7/10 of the way between the curves corresponding to 0.003 and 0.004. Then for the angle α

$$\frac{I_\alpha}{I_0} \sin \alpha = 0.0037.$$

The values of $I_\alpha/I_0 \sin \alpha$ may be quickly obtained for each desired value of the angle α. These are then plotted as described above. The procedure beyond this point is identical with that described earlier. The use of this chart at USRL has indicated that it is as accurate in general as a direct computation and the work proceeds much more quickly, particularly since most field data for instruments give directly 10 log I_α/I_0 rather than I_α/I_0.

In the above, it is assumed that the pattern has been drawn with the maximum on the outer circle on the coordinate paper. If the maximum is drawn on the circle which is 10 db down, the chart may still be used in the same way, but the values obtained for $I_\alpha/I_0 \sin \alpha$ from the chart should be multiplied by 10 to obtain the correct values; if the maximum is on the circle 20 db down, the chart values must be multiplied by 100, etc.

The chart can also be applied to a line. In this case it is turned so that 90 degrees on the chart coincides with 0 degrees on the directivity pattern. Since the chart in that direction is narrower, it will be necessary to plot the pattern on a smaller scale in order that the chart may accommodate it.

If the beam width is not too broad (total beam width 10 db below peak does not exceed 120 degrees), and the side lobes and rear response are at least 15 db below the peak, the directivity index is practically determined by the beam width alone. Thus, in Figure 7 the directivity index is plotted for a circular plate as a function of the beam width. By referring to this chart, one may read directly the directivity index for the measured beam width.

Many devices do not have directivity patterns symmetrical about a single axis. In general, then, directivity patterns would have to be measured in a great many planes passing through the acoustic axis, and a laborious double numerical integration performed to obtain the directivity index. In some cases where the pattern is symmetrical with respect to two perpendicular planes passing through the acoustic axis,

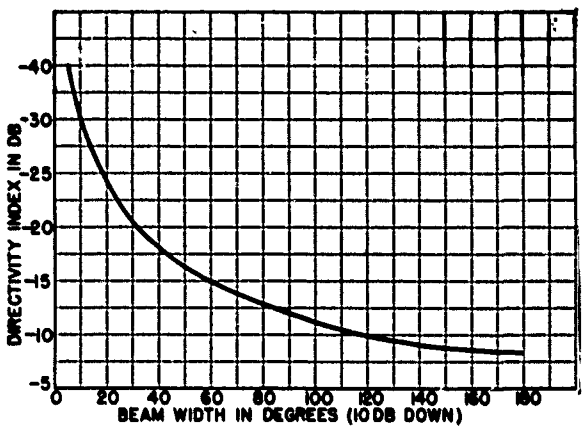

FIGURE 7. Directivity index as a function of the beam width for a circular plate.

an approximate value for the directivity index may be obtained by a simple procedure which requires taking directivity patterns only in these two planes. It is further required that the beam widths in these two planes be less than 120 degrees. To illustrate this method, let us consider a rectangular piston which is the most commonly occurring nonsymmetrical type in practice. For such a piston, the directivity index given is directly determined only by the beam width in the two planes and can be represented as a function of this beam width. For this case, a chart is given in Figure 8, from which the directivity index can be found from the measured beam width, 10 db down, in the two planes. The two planes in this case are the the planes passing through the acoustic axis and parallel respectively to the two pairs of sides of the rectangle. A similar calculation can be made for an elliptical piston when the two planes are taken through the acoustic axis and parallel respectively to the major and minor axes of the ellipse. A chart for this case also is given in Figure 8. These charts may be used in conjunction with measured patterns for rectangular or elliptical transducers.

Consideration has been given to reduction of side lobes by means of *tapering*. (See reference 14.) By tapering is meant the variation of the velocity distribution over the diaphragm of the transducer so that the velocity decreases from the center to the periphery. This method is quite effective for reducing side lobes, but it has the undesirable effect of increasing the beam width. The methods described above for calculating the directivity index can in general be applied directly to tapered transducers. The effect of

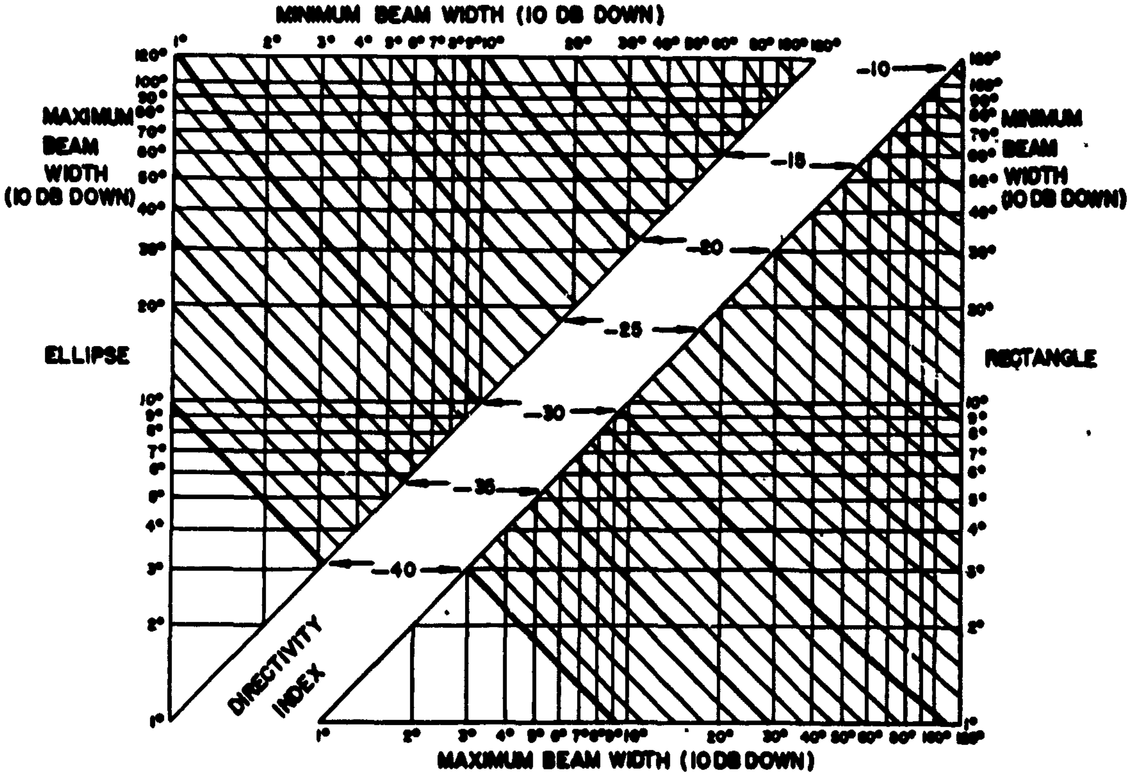

FIGURE 8. Directivity index as function of beam widths for rectangular and elliptical pistons. Maximum beam widths are measured in the plane through the acoustic axis parallel to the short side of the rectangle or including the minor axis of the ellipse. Minimum beam widths are measured in the plane through the acoustic axis parallel to the long side of the rectangle or including the major axis of the ellipse.

tapering on the directivity index, however, except in extreme cases, is relatively small.[b]

The following additional information can be obtained from the directivity pattern:

1. The *angle of maximum response* is the angle between the direction of maximum response and the acoustic axis.

2. *Beam width* may be defined as the angular separation between the two points on either side of the main beam which are 10 db below maximum.

3. *Height of side lobes* may be expressed in terms of the maximum pressure in any direction within the side lobe in decibels versus the pressure on the axis.

4. *Rear response* is defined as the maximum pressure within ±60 degrees from the rear in decibels versus the pressure on the axis.

It should be noted in this connection that, provided the device is linear, the directivity patterns and the directivity indices for transmitting and for receiving are identical at each frequency. This follows from the reciprocity principle.

4.1.4 Projector Efficiency

Another criterion which can be derived from the response and directivity measurements is of special interest to the designer because in the most fundamental way it rates his design as an electric motor delivering acoustic power for the electric power supplied. This criterion is the projector efficiency, defined as follows:

The projector efficiency is the ratio in decibels of the total acoustic power delivered by the projector to the electric power input into the projector.

To compute the efficiency E_p of the projector it is necessary to know the transmitting response R_T, the directivity index Δ, and the projector impedance z. The projector efficiency[59] then is given by

$$E_p = R_T + \Delta - 10 \log \frac{P_I}{P_A} - 70.9. \qquad (8)$$

[b] It has been shown by E. Gerjuoy that the directivity index of a circular plate has its optimum value when no tapering is used.

In connection with these measurements, reference should be made to the discussion at the beginning of this chapter where are stated certain precautions that must be observed in taking the data in order to obtain a precise determination of the efficiency.

It is shown later in this chapter that, when the device is linear, the projector efficiency is the same on transmitting and on receiving. This further illustrates the fundamental nature of this quantity.

4.1.5 Selectivity

The above quantities relate to the transmitting performance of the device at any one frequency. In general, however, the performance over a range of frequencies is of interest. In that case, the response and efficiency are determined over the frequency range and plotted versus frequency to provide response or efficiency characteristics. Directivity patterns may also have to be taken at several frequencies.

The response characteristic in particular is used to study the selectivity of the device. For this purpose use is frequently made of the *equivalent series resonant circuit*. This circuit is one in which the current varies with frequency in the same way that the response does. Assume this circuit to have resistance r and reactances $L\omega$ and $\frac{1}{C\omega}$ (where $\omega = 2\pi f$). Its impedance then is

$$z = r + j\left(L\omega - \frac{1}{C\omega}\right).$$

Since at resonance $\omega_0^2 = 1/LC$,

$$z = r + j\,L\omega\frac{\omega^2 - \omega_0^2}{\omega^2}.$$

The ratio of the resistance r to the reactance x in this circuit is

$$\left|\frac{r}{x}\right| = \frac{r}{L\omega\left(\frac{\omega^2 - \omega_0^2}{\omega^2}\right)}; \qquad \frac{L\omega}{r} = \left|\frac{x}{r}\right|\left(\frac{\omega^2}{\omega^2 - \omega_0^2}\right).$$

There are two values, ω_1 and ω_2, one on each side of resonance ω_0, where $x = r$. Then $|z_1| = |z_2| = r\sqrt{2}$. At resonance, that is, at ω_0, we have $x = 0$, so that $z_0 = r$. In addition because of symmetry $\omega_0 = \sqrt{\omega_1\omega_2}$, so that

$$\frac{L\omega_0}{r} = \frac{\omega_0}{\omega_1 - \omega_2} = \frac{f_0}{f_1 - f_2}.$$

For constant applied voltage e, the currents then are

$$i_1 = i_2 = \frac{e}{r\sqrt{2}}, \text{ and } i_0 = \frac{e}{r}.$$

Hence

$$20 \log\frac{i_1}{i_0} = 20 \log\frac{i_2}{i_0} = 20 \log\frac{1}{\sqrt{2}} = -3 \text{ db}.$$

The symbol Q has been used for the ratio $L\omega_0/r$. Usually in a resonant circuit the resistance is associated with the coil. The Q of the coil then is its quality or figure of merit.[83] To obtain the Q of a response curve, first the frequencies f_1 and f_2, at which the response is 3 db below the peak, and the resonant frequency f_0 are found; then Q is found from these three frequencies by means of the above relation:

$$Q = \frac{f_0}{f_1 - f_2}. \tag{9}$$

4.2 RECEIVING

An underwater acoustic device which is used only for receiving is called a hydrophone. The measurements on receiving usually involve determination of the following factors:

1. The voltage delivered by the device. This is referred to the condition in which the unit is in a uniform, plane sound field of reference pressure (1 dyne per sq cm).
2. The variation of this voltage with direction of sound incidence.
3. The variation of the voltage with frequency.

These factors are analogous to those tested on transmitting. There is another quantity of interest on receiving, the threshold pressure. This denotes the pressure on the face of the hydrophone that generates a voltage equal to its inherent noise voltage. This is related to the minimum signal that can be measured with the particular instrument. Of these quantities only the receiving response and the threshold are considered in detail, since the other items have been covered on transmitting.

4.2.1 Receiving Response

The receiving response of a hydrophone or a projector is expressed in terms of the open-circuit voltage

in decibels versus 1 volt, generated by the unit in a uniform plane-wave, free sound field of reference pressure (1 dyne per sq cm) propagated parallel to the acoustic axis of the hydrophone.

The selection of the open-circuit voltage has the advantage that, with a few exceptions noted below, it is possible to compute the signal voltage across any load impedance when the open-circuit voltage e_g and the impedance z of a projector or a hydrophone are known. For instance, if the load impedance is z_L, the voltage across it is

$$V = \left|\frac{e_g}{z + z_L}\right| z_L.$$

For certain types of hydrophones, designed for special purposes or including a preamplifier of the cathode-follower type, it is desirable to state the closed-circuit voltage instead of the open-circuit voltage. The load impedance across which the voltage is measured must be stated in all such cases.

In order to measure the open-circuit voltage, a very high impedance circuit is required, especially when dealing with crystal hydrophones, which have high impedances themselves. Frequently the measurements are made in a closed circuit and then the circuit loss is allowed for. In hydrophones which have a preamplifier associated with them, a small resistance is frequently included in the so-called calibration circuit to permit computing the open-circuit voltage generated by the crystal. Care must be taken in connection with the measurement of the response of such hydrophones that the output of the preamplifier is properly terminated. This applies especially to the so-called cathode-follower circuit which is commonly used.

Formulating a mathematical expression for the receiving response, we have

$$R_R = 20 \log \frac{e_g}{p} \tag{10}$$

where e_g = the generated voltage of the hydrophone in volts, and p = the pressure in the free field sound field in dynes per sq cm.

Instead of obtaining the open-circuit voltage, the group at the Woods Hole Oceanographic Institution prefer to calibrate their tourmaline gauges in terms of the electric charge on the crystal. This calibration is made by comparing the voltage V_P across the amplifier input (or output) due to a known pressure on the crystal, with the voltage V_O across the amplifier input (or output) due to a calibrating voltage V_g applied across the amplifier input in series with a known calibrating condenser C_R. The charge on the crystal due to the applied pressure can then be computed from the above mentioned voltages and the calibrating capacity. If the calibrating condenser C_g is in parallel with the crystal when the voltage V_P is measured,

$$Q = \frac{V_P\, V_R\, C_R}{V_C}.$$

From this charge Q and the capacity of the crystal C_0, the open-circuit voltage e can then be found.

$$Q = e_g C_0.$$

The determination of the charge instead of the generated voltage is convenient at times because it requires only measurements at the input or output of the amplifier, and the results are independent of the length of the intervening cable.

4.2.2 Threshold Pressure

The threshold of a hydrophone or a projector will be expressed in terms of the pressure in a uniform, plane-wave, free sound field propagated parallel to the acoustic axis of the device, in decibels versus reference pressure (1 dyne per sq cm), which produces a signal voltage equal to the inherent noise voltage. This noise voltage is taken in a band width of 1 cycle and the device is supposed to be in a matched, tuned circuit.

In the following, the significance of the term *threshold* is discussed and the measurements and computations necessary to obtain the threshold pressure are outlined.

The signal pressure which can be measured with any given device is limited in two directions: overloading limits it on the upper side, and the noise level limits it on the lower side. The noise may be due to a number of factors, such as the associated preamplifier, pickup in the leads, improper grounding, and contacts. When these sources are eliminated there remains thermal noise,[70] which is fundamental and depends only upon the temperature and the frequency range covered. The mean square value of this random noise voltage has been determined experimentally and theoretically. When reduced to a fre-

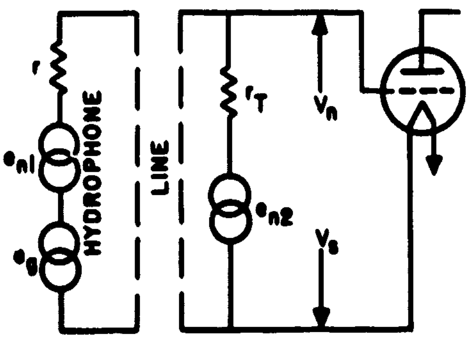

FIGURE 9. Circuit equivalent to a long line.

quency band of 1 cycle and a temperature of 20 C it has the value

$$e_n^2 = 1.61 \times 10^{-20} r_e, \tag{11}$$

where r_e is the equivalent series resistance of the device.

In the practical case there are two distinct conditions to be considered: calculated threshold and measured threshold.

Calculated Threshold

In the case of low-impedance hydrophones, usually of the electrodynamic or magnetostrictive type, the active unit usually is directly connected to a line.

If this line has appreciable length, its impedance must be matched at both terminals, since otherwise irregularities in response are introduced due to reflections in the line itself. Neglecting attenuation, the circuit may then be represented as in Figure 9.

Here e_g is the generated open-circuit signal voltage, e_{n1} is the generated noise voltage in the resistance of the hydrophone r, and e_{n2} is the generated noise voltage in the terminating resistance r_T. Reactances in the circuit are omitted for the sake of simplicity. V_n is the noise voltage and V_s is the signal voltage applied to the input of the measuring circuit, assumed to be the grid of the amplifier.

The noise voltage applied to the grid due to e_{n1} is

$$V_1 = \left(\frac{e_{n1}}{r + r_T}\right) r_T.$$

The noise voltage applied to the grid due to e_{n2} is

$$V_2 = \left(\frac{e_{n2}}{r + r_T}\right) r.$$

The rms noise voltage V_n applied to the grid due to both e_{n1} and e_{n2} is obtained by adding the two fluctuating noises at random phase, thus

$$V_n^2 = e_{n1}^2\left(\frac{r_T}{r + r_T}\right)^2 + e_{n2}^2\left(\frac{r}{r + r_T}\right)^2. \tag{12}$$

When the line impedance is matched at the two terminals, $r_T = r$. Then by equation (11) above, $e_{n1} = e_{n2} = e_n$, so that

$$V_n^2 = \left(\frac{e_n}{2}\right)^2 + \left(\frac{e_n}{2}\right)^2$$

$$V_n = \frac{e_n}{\sqrt{2}}. \tag{13}$$

The signal voltage V_s applied at the grid is then one-half the voltage generated by the hydrophone,

$$V_s = \frac{e_g}{2}.$$

From the above relation V_s, the signal voltage generated by the hydrophone, equals V_n, the noise voltage in the matched circuit, when

$$e_g = 1.41\, e_n. \tag{14}$$

The other possibility, instead of matching the circuit, is to connect the hydrophone to a very high impedance. In that case r_T is very large relative to $r (r_T \to \infty)$. Hence from equation (12)

$$V_n^2 = e_{n1}^2 \tag{15}$$

and the signal voltage V_s applied to the grid becomes

$$V_s = e_g$$

so that

$$e_g = e_{n1}. \tag{16}$$

It is seen by comparing equations (14) and (16) that there is a theoretical gain in the signal-to-noise ratio of 3 db in terminating the hydrophone in a high impedance as compared to matching it. Where the leads are sufficiently short it is therefore advantageous to use a high-impedance termination. This applies especially to the internal connection between the active

unit and its preamplifier, a case which is discussed below.

The threshold pressure for low-impedance hydrophones may be computed from the receiving response R_R and the resistance of the hydrophone r. This relation is as follows:

Substituting in the above equation (14) for e_n, the value given by equation (11) leads to the results

$$e_s = 1.79 \times 10^{-10}\sqrt{r}. \qquad (17)$$

The signal voltage is related to the signal pressure p (in dynes per sq cm) by means of the receiving response R_R, in accordance with equation (10),

$$R_R = 20 \log\left(\frac{e_s}{p}\right),$$

which may be written in the form

$$20 \log p = 20 \log e_s - R_R.$$

Introducing in this equation the signal voltage defined by equation (17), we obtain the threshold pressure in decibels

$$T = 20 \log p = 20 \log (1.79 \times 10^{-10}\sqrt{r}) - R_R$$
$$= 10 \log r - 194.9 - R_R. \qquad (18)$$

The test procedure in accordance with the above is to measure the resistance and response of the hydrophone. From these values the threshold pressure then is computed by means of equation (18).

Measured Threshold

For a high-impedance hydrophone of the crystal type, the active element is usually directly associated with a preamplifier. This is necessary in order to avoid excessive losses in the leads and also to prevent noise pickup, to which a high-impedance circuit is apt to be subject. Frequently the preamplifier is given an extremely high input impedance. This is done in order to obtain the maximum signal-to-noise ratio at the first grid (as discussed) and also in order to stabilize the hydrophone. For instance, in the case of x-cut Rochelle salt crystals, which are inherently variable with temperature, the variability is reduced when no current is drawn from them.

Since the preamplifier is so intimately associated with the active element, it is best to treat the two as one unit and to determine the threshold for the combination. As a rule, the noise of the preamplifier exceeds the thermal noise to such an extent that the latter has little practical importance. The computation outlined above then becomes useless and the only practical way to proceed is actually to measure the inherent noise level of the instrument. This requires an extremely quiet body of water and a very quiet measuring system in order that extraneous noise does not enter into the tests. When quiet water is not available, a possible alternative is to substitute a network for the crystal. The latter must be the electrical equivalent of the crystal in water over the entire frequency range included in the measurement. The measuring system, in addition, should have uniform response and a definitely defined band width, narrow enough so that variations in the hydrophone response within the band may be neglected. Usually the preamplifier output is matched. If the measuring band includes the frequencies from f_1 to f_2, then the value $10 \log (f_2 - f_1)$ must be subtracted from the measured noise voltage (assuming it to be in decibels), in order to obtain the threshold.

4.3 RELATIONS BETWEEN MEASUREMENTS

In the following, certain relations that exist between the measured quantities are pointed out.[59] These relations frequently are useful in cross-checking measurements. They also reveal additional information as to the nature of the definitions.

1. The relation between the projector efficiency E_p and the transmitting response R_T was given in equation (8):

$$E_p = R_T + \Delta - 10 \log \frac{P_I}{P_A} - 10 \log \frac{\rho c 10^7}{4\pi d^2}$$
$$= R_T + \Delta - 10 \log \frac{P_I}{P_A} - 70.9.$$

2. There was also given the relation between the calculated threshold and the receiving response R_R in equation (18)

$$T = 10 \log r - 194.9 - R_R.$$

3. There exists, in addition, a reciprocal relation[c] between the transmitting response and the receiving response of a projector. This relation has the following form:

$$R_T = R_R + 20 \log f + 10 \log \frac{P_I}{P_A} - 10 \log r + 20 \log \frac{\rho 10^7}{2d}$$

$$= R_R + 20 \log f + 10 \log \frac{P_I}{P_A} - 10 \log r + 94.2. \tag{19}$$

4. From these three equations, it is possible to derive a relation between the projector efficiency E_p and the threshold T:

$$E_p + T = \Delta + 20 \log f + 10 \log \frac{\rho\pi 10^7}{c} - 194.9$$

$$= \Delta + 20 \log f + 171.6. \tag{20}$$

5. Furthermore, by combining equations (18) and (19) or (8) and (20), a relation can be obtained between the threshold T and the transmitting response of the unit R_T. This relation is as follows:

$$R_T + T = 10 \log \frac{P_I}{P_A} + 20 \log f + 20 \log \frac{\rho 10^7}{2d} - 194.9$$

$$= 10 \log \frac{P_I}{P_A} + 20 \log f - 100.7. \tag{21}$$

6. Finally, by combining equations (8) and (19) a relation can be found between the projector efficiency and the receiving response of the device:

$$E_p = R_R + \Delta + 20 \log f - 10 \log r + 10 \log \frac{\rho\pi 10^7}{c}$$

$$= R_R + \Delta + 20 \log f - 10 \log r + 23.3. \tag{22}$$

The following discussion has for its purpose the exploration of the meaning of the above relations and the indication of their usefulness in connection with the study of measured data. For the sake of simplicity the discussion is confined to circular pistons.

In the case of a circular piston moving rigidly in an infinite baffle, there exists a simple relation between its radius a and the directivity index Δ.[28]

$$\Delta = -10 \log \frac{k^2 a^2}{\left[1 - \frac{2J_1(2ka)}{2ka}\right]}, \tag{23}$$

where $k = 2\pi/\lambda$, λ being the wave length $= c/f$, and J_1 = first order Bessel function.

The directivity of a physical projector usually is less than that of a theoretical circular piston of the same geometrical size. It is, however, possible to define the *effective* or *acoustic radius* of the physical projector to be the radius of the theoretical piston having the same directivity index as the projector. On Figure 10 the directivity index and beam width are plotted against effective radius in wave lengths (a/λ) for a theoretical piston.

A number of interesting relations are obtained by introducing this expression in the above equations in which the directivity index occurs. These are the equations which include the projector efficiency. For instance, substituting the above expression for the directivity index in the relation between projector efficiency and transmitting response, equation (8) gives:

$$E_p = R_T - 10 \log \frac{\pi a^2}{\left[1 - \frac{2J_1(2ka)}{2ka}\right]} - 10 \log \frac{P_I}{P_A} + 20 \log \lambda - 10 \log \frac{\rho c 10^7}{d^2}$$

$$= R_T - 10 \log \frac{\pi a^2}{\left[1 - \frac{2J_1(2ka)}{2ka}\right]} - 10 \log \frac{P_I}{P_A} + 20 \log \lambda - 81.9. \tag{24}$$

In the term $\frac{\pi a^2}{\left[1 - \frac{2J_1(2ka)}{2ka}\right]}$ in this equation, πa^2 is the area of the theoretical piston of radius a. In the case of an actual projector, in accordance with the above discussion, a is the effective radius and can be found by means of the chart on Figure 10. The expression in the bracket is a pure numeric, so that the whole term has the dimensions of an area. Let it be

[c] The reciprocity theorem and the conditions under which it applies are stated in Chapter 3.

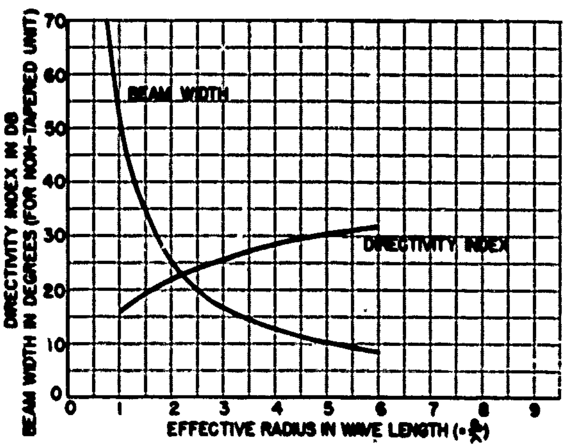

FIGURE 10. Relation between effective radius and directivity index (or beam width) for sonar projector with circular diaphragm.

called the *effective area of the projector*[d] A, which is thus defined

$$A = \frac{\pi a^2}{\left[1 - \frac{2J_1(2ka)}{2ka}\right]}. \qquad (25)$$

Defining the directivity factor δ by

$$\Delta = 10 \log \delta,$$

it is evident from equation (23) that

$$\delta = \frac{\left[1 - \frac{2J_1(2ka)}{2ka}\right]}{k^2a^2},$$

and from equation (25) that

$$A = \frac{\lambda^2}{4\pi\delta}. \qquad (26)$$

In case a exceeds one-half wave length, the term $1 - [2J_1(2ka)/2ka]$ is nearly unity, so that A then equals πa^2.

Assuming, furthermore, the transition loss to remain unchanged, we can simplify equation (24) by introducing a constant K_1,

$$K_1 = -\left(10 \log \frac{P_I}{P_A} + 81.9\right),$$

[d] The effective area was first defined in these terms by L. E. Teal of the Columbia University Underwater Sound Laboratory at New London in a letter dated February 23, 1943.

and write

$$E_p = R_T - 10 \log A + 20 \log \lambda + K_1. \qquad (27)$$

This expression shows that for constant projector efficiency, the transmitting response varies directly as the effective area, and for any given device (A = constant) increases 6 db per octave. The latter relation is shown by equation (21) to exist also for fixed threshold and transition loss.

Introducing the expression for the directivity index in equation (20) gives

$$E_p + T = -10 \log A + 10 \log \frac{\rho c 10^7}{4} - 194.9$$

$$= -10 \log A - 79. \qquad (28)$$

This equation shows that for any given device (A = constant) the threshold pressure is independent of frequency and also indicates that the higher the efficiency of the projector the lower the threshold pressure. For devices of the same type, that is, having the same efficiency, the threshold varies inversely as the size of the unit.

Substituting the above expression for the directivity index in equation (22) we obtain

$$E_p = R_R - 10 \log A - 10 \log r + 10 \log \frac{\rho c 10^7}{4}$$

$$= R_R - 10 \log A - 10 \log r + 115.9. \qquad (29)$$

From this equation it may be seen that for a given device having fixed size and efficiency, the receiving response is independent of frequency but increases directly with the resistance. Advantage is often taken of this latter fact by using a step-up transformer to increase the receiving response of a low-impedance hydrophone. These relations between receiving response and impedance are shown by equation (18) to apply also for a fixed threshold. It is also interesting to note that for a given receiving response and efficiency the resistance among different projectors varies inversely as their area.

It is, of course, possible to set up a definition for the receiving efficiency of a hydrophone or a projector. In terms analogous to those used for the projector efficiency given above, this efficiency could be stated

$$E_R = 10 \log \frac{P_E}{P_I}.$$

In this equation, the electric signal power delivered by the hydrophone in a matched circuit is

$$P_E = \frac{e_g^2}{4r}.$$

For the acoustic input power it is possible to take the product of the free field intensity, $p^2/\rho c$, and A, the effective diaphragm area, and obtain,

$$P_I = \frac{p^2}{\rho c} A \times 10^7 \text{ watts},$$

where p is the free field pressure. P_I is actually the *available acoustic power* in the water, which equals the actual acoustic input power if the device matches the medium and is sufficiently large so that diffraction can be neglected.

Introducing these values in the above equation for E_R, we obtain

$$E_R = R_R - 10 \log A - 10 \log r + 10 \log \frac{\rho c 10^7}{4}. \tag{30}$$

Comparing this expression with equation (29),

$$E_p = R_R - 10 \log A - 10 \log r + 10 \log \frac{\rho c 10^7}{4},$$

the important result is obtained, that $E_R = E_p$. Thus, a projector has the same efficiency on transmitting and on receiving.

Chapter 5

TESTING TECHNIQUE

By *Leslie L. Foldy*

5.1 THE TESTING PROBLEM IN GENERAL

5.1.1 Calibration and Operational Testing

The testing of underwater sound devices assumes two forms, depending upon the type of information desired. In one type of test, it is desired to obtain information which characterizes the device independent of its environment to such an extent that its behavior in any particular environment can be predicted. Such a test is known as a *calibration test.* On the other hand, when a device is to be used in a particular application, it is often desirable to obtain directly information bearing on its efficacy in carrying out an assigned task under the conditions which prevail in the particular application. Such a test is referred to as an *operational test.*

The difference in philosophy of the two types of tests is essentially the following: A calibration test is made under carefully controlled conditions, with the object of eliminating all extraneous factors entering into the measurement which represent characteristics of the environment rather than those of the device itself. In an operational test, on the other hand, environmental factors are of prime importance, since information is desired not on the intrinsic characteristics of the device but on its behavior in an environment closely approximating actual operating conditions. There is, of course, a relationship between the operational performance of a device and its inherent characteristics as determined by calibration measurements. Operational tests in general are beyond the scope of the activities of the Underwater Sound Reference Laboratories and the present discussion is largely limited, therefore, to testing technique in calibration measurements.

5.1.2 The Characterization of Transducers

Most calibration measurements on underwater sound equipment consist of measurements on transducers, so that principal interest is attached to these, although much of the discussion is applicable to measurements on domes, baffles, and similar auxiliary equipment. An important consideration in the calibration of a transducer is the information which is required to characterize the device. A linear, passive, electroacoustic transducer[a] is completely characterized when certain parameters and parametric functions are known as functions of frequency, as is shown in Chapter 3. When these relations are known, one can in principle compute the behavior of the device in any well-defined environment. However, neither the determination of the characteristic quantities nor the determination from these of the behavior of the instrument in even relatively simple environments can actually be carried through because of the complexities of the measurements and computations necessary. Fortunately, however, such a complete characterization is neither necessary nor desirable under most circumstances. In the majority of cases, most of the useful information about a transducer can be obtained by relatively simple procedures, and operational characteristics can be derived from these data in a relatively direct and simple manner.

The characterization of a transducer, as dictated by practical considerations, is summarized in Chapter 4. Therein are indicated the principal functional relationships whose measurement gives information which, if not complete, is at least sufficient to characterize a transducer and to allow its operational behavior to be evaluated for most cases of interest.

The intent of the present chapter is to indicate the means by which one may determine the *true values* of the quantities measured; in other words, it is to find the means by which the measured values may be corrected to make the results independent of the characteristics of the equipment, the location of the tests, etc. This problem presents two aspects: (1) to determine the conditions of the test so that local extraneous factors do not enter significantly into the measurements and, (2) where the above is not possible under the conditions present, to correct for the effects of local extraneous factors.

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[a] The definitions of these terms are found in Chapter 3.

The characterization of a transducer for practical purposes is usually effected by evaluating the following quantities: (1) receiving response as a hydrophone, (2) transmitting response as a transducer, (3) directivity pattern, and (4) impedance.

Receiving Response as a Hydrophone

The receiving response as a hydrophone is defined as the open-circuit voltage (in db vs 1 volt) generated by the hydrophone when placed in a uniform plane-wave sound field of reference pressure (1 dyne per sq cm) propagating parallel to the acoustic axis of the hydrophone. (See Chapter 4.) The *acoustic axis* of the hydrophone is an arbitrarily selected axis through the hydrophone, which is, however, usually chosen to be either some axis of symmetry for the instrument, the axis of maximum response, or some other readily identified axis. The plane-wave sound field of 1 dyne per sq cm should be, of course, the sound field when the hydrophone is not present, since the latter will in general distort the field by diffraction. If the hydrophone is linear, the voltage generated is proportional to the magnitude of the sound field, and the measurement may be made in a sound field of any magnitude and then reduced to its value for a reference field. In some cases, where it is not possible to measure the open-circuit voltage of a hydrophone, the voltage across some given impedance is measured. This voltage may or may not be reduced to an open-circuit voltage, depending on the circumstances.

Transmitting Response of a Transducer

A transmitter of finite size can be shown theoretically to produce a sound field such that the pressure along any axis of the transmitter, at sufficiently great distances from the transmitter, falls off directly as the distance from the transmitter. This region at sufficiently great distances is known as the inverse-square-law region, since the sound intensity falls off as the square of the distance. Close to the transmitter the sound field does not follow this law. Here a more complicated sound field distribution obtains, which depends upon the particular characteristics of the transducer. For most applications only the pressure produced in the inverse-square-law region is of importance.

The relationship between pressure and distance is given by

$$p = \frac{C_0}{d} \tag{1}$$

for points in the inverse-square-law region, where p is the pressure at a distance d from the transmitter on any axis through the transducer, and C_0 is a constant which may have different values for different axes.

The *transmitting response* of a transducer is defined as the pressure measured at a distance d in the inverse-square-law region on the acoustic axis of the transducer for 1 watt available power from a given generator impedance (assumed to be purely resistive), reduced to a distance of 1 meter by multiplication by d in meters, and expressed in db vs 1 dyne per sq cm. (See Chapter 4.) The *available power* of a generator is defined as the power delivered by the generator to an impedance which is the complex conjugate of its own impedance. Thus, if the generator has a purely resistive impedance r_g and a generator voltage e_g, the available power from the generator P_A is given by

$$P_A = \left(\frac{e_g}{2r_g}\right)^2 r_g = \frac{e_g^2}{4r_g}. \tag{2}$$

(See Figure 1 in Chapter 4.) For a linear transducer the generated pressure is proportional to the current into the transducer (independent of its impedance). Therefore, to characterize a transmitter on the basis of available power, it is necessary to know not only the impedance of the source but the impedance of the transmitter as well.

Directivity Pattern

The transmitting and receiving responses characterize the acoustic behavior of a transducer at long distances on its acoustic axis; however, information is also desired on the sound field produced in other directions. This information is provided by *directivity patterns*, which give the ratio in db of the response in any direction to the response on the axis. To characterize directions, it is necessary to set up a spherical coordinate system for the transducer. Referring to Figure 1, we take the Z axis along the acoustic axis of the transducer and choose the XZ plane in an arbitrary orientation which is usually selected to be the horizontal plane through the transducer in its normal operating position. The direction of any line can then be specified by the angle θ between the line and the Z axis, and the angle ϕ between the XZ plane and the plane through the Z axis and the line, as shown. To specify completely the directional pattern, the ratio of the response on every axis to that on the acoustic axis should be given. If the sound field is

rotationally symmetrical about the Z axis, however, only the pattern for lines in one plane (the XZ plane, for example) need be given. When this symmetry does not exist, measurements of the patterns in a few planes are usually sufficient for practical applications.

It may be noted from the definition that the directivity pattern may be obtained for both hydrophones and transmitters. For linear passive transducers which obey the reciprocity principle, the directivity patterns for the transducer in receiving and in transmitting are identical (see No. 4 in Section 5.5.7).

IMPEDANCE

The *impedance* of a transducer is defined as the complex (vector) ratio of the voltage across the terminals to the current into the transducer. (See Chapter 4.) The impedance depends upon the acoustic termination of the transducer, and in principle the impedance should be measured when the transducer is in an infinite medium—water, in particular.

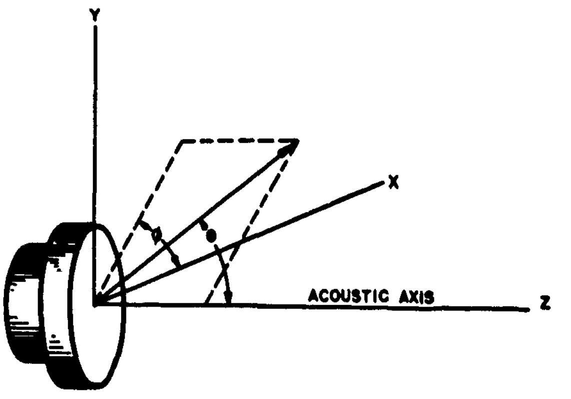

FIGURE 1. Coordinate system for transducer.

5.1.3 Ideal Testing Conditions

An examination of the preceding definitions indicates that, in order to measure properly the quantities discussed in strict accordance with their definitions, one must have (1) an infinite homogeneous medium in which to perform the tests, (2) a source of plane waves, and (3) no extraneous acoustic signals (ambient noise). While these ideal testing conditions are impossible to meet in actual practice, they provide, nevertheless, a useful standard with which to gauge and appraise actual testing conditions.

5.1.4 Compromises in Actual Testing Conditions

TESTING MEDIA

It is evident that no infinite homogeneous testing medium actually exists. If available bodies of water are considered, two departures from ideal conditions occur. Actual bodies of water are bounded by an air-water interface at the surface and by bottoms ranging in character from soft mud to rock. The influence of these boundaries on a calibration test lies in the fact that they reflect sound from the source so that the acoustic signal reaching a measuring instrument consists of the vector sum of the desired acoustic signal and these reflections. Depending on the relative phase and magnitude of these reflections, the measured signal magnitude may be greater or less than the acoustic signal which one desires to measure.

The obvious method of eliminating these effects would be to choose a site in which bounding surfaces are so distant from the testing locale that reflected signals would be negligible compared to the desired signal. Although this is a feasible compromise, there are limits dictated by other circumstances as to how far one can go in this direction. One of these, representing the second departure from ideal conditions in actual media, is the lack of acoustical homogeneity of available bodies of water over large distances. These inhomogeneities are most often due to temperature gradients in the medium, although other effects, such as variations of salinity and increase of hydrostatic pressure with depth, are sometimes significant. The effect of these is to cause refraction of the acoustic signal, thus disturbing the desired acoustic geometry of the test and in general introducing unknown factors which influence the measurements.

PLANE WAVES

The only means by which one can generate truly plane waves in an infinite medium is by means of an infinite plane radiator. However, at sufficiently large distances in a homogeneous medium, all sound generators of finite size produce waves for which the surfaces of constant phase are concentric spheres. If the amplitude of the waves does not change appreciably over the volume occupied by the device being tested, and if the radius of the spheres of constant phase at the test position is sufficiently large compared to the dimensions of the device, then for all practical purposes the wave field in the region may be considered as plane. The greater the testing distance, the more

nearly is this the case. The testing distance is limited, however, by the interfering reflections which arise at the bounding surfaces of medium. A compromise between these two factors must be effected, and much of the later discussion centers around this point.

AMBIENT NOISE

To insure that only the desired signal is being measured, it is necessary that the ambient noise, which is invariably present in any body of water, be of sufficiently low level compared to the level of the desired signal. In this matter, the best that may usually be achieved is the selection of a site where ambient noise is naturally low. When calibrating receivers, a further gain may be realized by using transmitters which can deliver an acoustic signal of sufficiently high level to make the effect of ambient noise of negligible importance.

5.1.5 Necessity for Testing Technique

The preceding discussion indicates that the specific manner in which a test is conducted is usually a compromise among several competing extraneous effects which tend to prevent a measurement under ideal testing conditions. The purpose of a doctrine of testing technique is to provide a body of rules to aid in determining the most advantageous compromise in the choice of such factors as testing site, depth, and distance, and thus to permit the most accurate measurement possible of the quantities desired. These rules are based partly on theoretical considerations and partly on general experience in such measurements. They may play as important a part in determining the accuracy of the results as the quality of the testing equipment available. In fact, a lack of appreciation for these rules often introduces far greater errors in a measurement than any other factor.

5.2 SELECTION OF TESTING SITE

5.2.1 Available Sites

The first question which arises in a program of calibration testing is the choice of a site for the measurements. Available sites usually fall into the following five groups:

1. *Oceans and large lakes.* These may be characterized as bodies of water many miles in extent and more than 100 feet in depth. They are of sufficient size so that, except in relatively calm weather, surface waves of more than 1 foot in height are usually present. To reach great depths one must usually go at least several thousand feet out from shore.

2. *Small lakes.* Inland bodies of water ranging from 200 yards to several miles across may be classified as small lakes. Their depths may vary greatly but rarely exceed 100 feet. Surface waves are relatively small and, in many cases, considerable depth may be reached within 50 to 100 feet from shore.

3. *Natural or artificial ponds.* Bodies of water up to about 200 yards across, with various depths usually less than 50 feet and with relatively small surface waves, are classified as natural or artificial ponds.

4. *Rivers.* Although rivers vary greatly in character, they have more or less steady water currents. They have depths rarely exceeding 50 feet and, if navigable, usually carry considerable water traffic.

5. *Tanks.* Tanks are usually internally housed structures of relatively small dimensions. For purposes of further discussion, swimming pools may be considered as tanks.

5.2.2 Factors Entering Into Choice of Site

Certain factors entering into a choice of testing site in relation to compromises in actual testing have been previously discussed, and are now considered in detail along with other factors.

SIZE

The factor of size enters into the choice of site in two ways: in its direct effect on measurements caused by reflections from the surface, shore, bottom, etc., and indirectly in its determination of other factors such as homogeneity of the medium, ambient noise level, accessibility, and rigging considerations. If these latter considerations were not important, the largest and deepest body of water available would be the most preferred, for it would then approach most closely to an infinite medium, and the effect of interfering reflections could be essentially eliminated. Actually, however, a compromise must be effected among these various factors.

TYPE OF BOTTOM

The surface of a body of water being in almost all cases an air-water interface which reflects sound almost completely, there is not much choice in this consideration. However, the type of bottom which is present may often be of importance. Types of bottom

available may be classified as mud, sand, and rock. The last is the least desirable, since it is usually a good reflector. A soft mud bottom which does not contain gas bubbles is probably the most desirable of the three. However, most soft mud bottoms contain organic material whose decay produces bubbles of gas. Part of this gas remains entrapped in the mud and makes it a relatively good reflector.

A fine sand or silt may be fairly absorbing. It has been found, for example, that the fine sand bottom at Lake Gem Mary in Orlando is a better absorber for sound than the soft mud bottom at Crystal Lake in Mountain Lakes. The inferiority of the latter has been traced to the presence of gas bubbles in the bottom. No satisfactory method has been found to inhibit permanently the decay which produces the bubbles, but repeated dredgings can keep the bottom in a satisfactory state.

Transmission and bottom reverberation measurements at sea also have indicated that rock, sand, and mud are successively better absorbers, in the order of listing.

Ambient Noise

The ambient noise present in the water at a testing site determines the minimum signal pressure which can be measured at the locations. Ambient noise is usually not a significant factor in measurements except when the transmitters used have a sound output limited to low values. Ambient noise also determines the lower limit at which inherent self-noise measurements on transducers may be made.

The ambient noise at a testing site may be due to many factors. It may be produced by waves on the surface or lapping against the shore (particularly in rough weather), underwater life, water traffic, airborne sound, rain, or various other sources. Hence, to keep the ambient noise as low as possible, one should choose a location where waves are relatively small, no water traffic is present, and noise-producing underwater life is absent. Small lakes, ponds, or tanks meet these conditions best.

Accessibility and Weather

An obvious but important consideration in choosing a testing site is the accessibility of the site itself. If one goes to a large lake or ocean and testing is done far from shore, the matter of transportation to the testing site becomes important. Furthermore, testing may be made impossible at such a site in any but fair weather so that the time available during the year for testing may be relatively short. In small lakes, ponds, or tanks, this is much less of a problem, and it has been found that on small lakes testing may proceed satisfactorily except during heavy storms. A homely but significant factor, if testing is done from ships or barges in large bodies of water, is the possibility of seasickness among the testing crew in any sort of weather where pitching or rolling of the vessel occurs.

Temperature Gradients

Temperature gradients in water are usually of the same order of magnitude, regardless of the size of the body of water. The general effect of temperature gradients is the refraction of the sound beam. The most effective remedy is to work at testing distances as short as possible. Consequently a location where other factors allow a short testing distance is in general more satisfactory from the point of view of temperature gradients. Climatic conditions conducive to minimizing temperature gradients in water are to be preferred. These include cloudy days, rough water, or ice on the surface. The last two interfere, of course, with other aspects of calibration.

Rigging Considerations

By *rigging* is meant the general mechanics of holding transducers and auxiliary equipment in a particular location and with particular orientation. The testing site has some influence on the problems of rigging. For many tests, it is necessary to maintain instruments at a constant distance apart and to maintain constant their relative orientation. This problem is simplified if the rigging is done from a rigid structure. Therefore, piers are more satisfactory testing locations than ships or barges, so far as ease of rigging is concerned. When rigging is done from a ship or barge, the supporting structures require additional rigidity because of pitching and rolling of the vessel. In addition, a pier allows vertical hanging of an instrument with comparative ease. The greater the testing depth, the more difficult it is to provide a rigid structure to maintain instruments at their locations. Thus, the advantages of working at great depth to avoid surface reflections are partly vitiated by the additional difficulties in rigging.

Location of Test Equipment

In the performance of calibration tests, there is

required, in addition to the transducers used in the tests, a considerable amount of auxiliary electrical equipment such as amplifiers, modulators, impedance bridges, and recorders. This equipment should all be located in relative proximity to the transducers which are used, so that transmission losses occurring in the propagation of electrical signals from transducers to measuring instruments are as small as possible. If possible, it is most satisfactory to have the electrical measuring equipment directly over the testing location, although signals may be transmitted from the end of a short pier without serious loss. Transmission of signals from a barge to shore, however, may not be as satisfactory as is to be desired. Thus, the location of the test equipment should be taken into account in selecting a test site.

5.2.3 Small Lakes as Testing Sites

In Sections 5.2.3, 5.2.4, and 5.2.5, the relative advantages and disadvantages of the various available testing sites are discussed. USRL has largely confined its testing to small lakes and indoor tanks. The former have been found to be a relatively satisfactory type of site for calibration testing. While they have certain disadvantages, the methods developed to compensate for these have proved quite successful.

The principal disadvantage of a small lake is its relatively shallow depth and, in some cases, its small size. This usually limits the testing distance that can be used, principally because of reflections from the surface and bottom. However, methods described later in this chapter have made it possible to eliminate, to a considerable extent, the effect of these reflections on tests, except at relatively low frequencies (principally below 10 kc). On the other hand, a small lake has the advantages of low ambient noise level and the possibility of working in all but very bad weather.

If testing is done from a pier, as is usually the case at Mountain Lakes and Orlando, the problem of rigging for tests is fairly easily solved, and equipment may be located on shore without introducing serious transmission line problems. Small lakes are also usually free from rapid currents and tides, thus simplifying the problem of rigging even more. While temperature gradients of sizable magnitude occur in small lakes, the small testing distances which are used (rarely over 50 feet) reduce the effect of this factor to relative insignificance.[b] A general disadvantage of all outdoor testing sites is the fact that the temperature of the water cannot be controlled, as it is determined by climatic and weather conditions.

In general, the same considerations apply to ponds as to small lakes, but the relatively smaller size introduces the difficulty that reflections from the shore may be quite serious, especially in such tests as the rear response of highly directional projectors. On the whole, however, small lakes probably provide the most generally satisfactory outdoor testing sites for calibration testing.[c]

5.2.4 Large Bodies of Water and Rivers as Testing Sites

The principal advantage of a large body of water, such as the ocean or a large lake, is the great depth which usually can be attained. This reduces interfering reflections and permits the use of greater testing distances, thereby eliminating proximity effects in calibration.

The number of disadvantages is quite large, however. The ambient noise level is generally high because of large waves and water traffic. Accessibility becomes a serious problem and is usually severely limited by weather conditions. The rigging of test devices at sufficient depths to realize the advantage of deep water is a major problem. Long rigid suspensions must be employed and these must be of sufficient strength to withstand the bending moments induced by rolling and pitching of the vessel from which the instruments are suspended. Large vessels must be employed if the greater testing distances are to be attained, while if two separate vessels are used to support the receiver and transmitter, the problem of maintaining relative orientations becomes exceedingly serious. The effect of thermal gradients also becomes important. On the whole, it may be said that such difficulties make it inadvisable to employ large bodies of water as test sites for calibration work, although they are essential to operational testing.

Rivers suffer many of the disadvantages of oceans or large lakes, such as a high ambient noise level due largely to water traffic, frequent periods of inacces-

[b] Other laboratories have sometimes indicated considerable trouble caused by temperature gradients, but this has not been the experience at the USRL test stations.

[c] Experience has indicated that there is no appreciable difference in the behavior of underwater sound equipment in fresh water as compared to sea (salt) water.

sibility, and difficulties in satisfactory rigging, which are increased by water currents. In general, the advantages of a river, without the disadvantages, may be realized just as satisfactorily in a lake of proper size.

5.2.5 The Use of Acoustic Tanks for Testing

A disadvantage presented by all natural testing sites is that the temperature of the water cannot be controlled. The hydrostatic pressure can be controlled somewhat by the choice of testing depth but is limited by the depth of water at the location and by other factors, such as rigging problems. In the calibration of many devices, the determination of the temperature and pressure dependance of certain of their characteristics is both desirable and necessary, since many of these devices must be operated in water temperatures ranging from near-freezing to tropical and at hydrostatic pressures corresponding to depths of several hundred feet of water. The only satisfactory method of making such measurements seems to be by the use of an acoustic tank. The principal disadvantage of tanks is their small size, which causes interfering reflections and limited testing distances. However, if the inner surfaces of the tank can be coated with some sound-absorbing material, or if a pulsing technique in measurement can be employed, a tank may form a satisfactory testing site. It has the advantage of having low ambient noise, accessibility independent of weather, and simplified rigging, in addition to temperature and pressure control. The characteristics of particular tanks that have been constructed are treated elsewhere in this volume.

5.3 ELIMINATION OF REFLECTIONS

5.3.1 General Considerations

It was pointed out previously that acoustic reflections from the surface, bottom, or shores of a body of water, or from other reflecting objects such as pilings used to support a pier or dock from which tests are made, interfere with the calibration of instruments since they make it difficult to establish a plane progressive sound wave. Receivers in such cases measure not only the pressure or pressure gradient due to the desired wave from the source, but also the contributions of reflected waves to the pressure or pressure gradient. The superposition of the direct wave and reflected waves produces in the medium a complicated standing wave pattern, whose configuration changes as the frequency is varied. Thus, if a nondirectional (pressure-sensitive) receiver is used to measure the pressure at a point in the resultant field, the measured pressure oscillates about the pressure in the direct wave as the frequency is varied. Assuming the surface to be perfectly reflecting, which is very closely true in many tests, the expression for the pressure at a horizontal distance d from a point source at a depth h and with an operating frequency f is

$$p = \left[p_0^2 + \frac{p_0^2 d^2}{d^2 + 4h^2} - \frac{2p_0^2 d}{(d^2 + 4h^2)^{1/2}} \cos \frac{2\pi f}{c}\left(\sqrt{d^2 + 4h^2} - d\right)\right]^{1/2}, \quad (3)$$

where p_0 is the pressure which would exist at the point in question if the water surface were not present, and c is the velocity of sound. Thus, as f varies, p oscillates between the values

$$p_0\left[1 + \frac{d}{(d^2 + 4h^2)^{1/2}}\right] \text{ and } p_0\left[1 - \frac{d}{(d^2 + 4h^2)^{1/2}}\right] \quad (4)$$

because of the cosine term. It will be noted that the oscillation of p with f becomes more violent as d becomes greater compared to h. These phenomena are well illustrated in Figure 2, where the voltage developed by an essentially nondirectional hydrophone in the field produced by an essentially nondirectional source is shown for several testing distances. For any fixed depth the interference minima are increasingly prominent as the testing distance is increased. The characteristic appearance of these interference maxima and minima is quite helpful in indicating when reflections are interfering in a test.

If the reflecting surface, which may be the bottom or any other surface, has a pressure reflection coefficient R, then equation (3) is modified to

$$p = \left[p_0^2 + \frac{R^2 p_0^2 d}{d^2 + 4h^2} - \frac{2R^2 p_0^2}{(d^2 + 4h^2)^{1/2}} \cos \left\{\frac{2\pi f}{c}\left(\sqrt{d^2 + 4h^2} - d\right) - \alpha\right\}\right]^{1/2}, \quad (5)$$

where α is the phase shift on reflection. Hence, by reducing the reflection coefficient of the surface, one

may reduce the magnitude of the response variation. An air-water interface has a reflection coefficient close to unity, but a muddy or sandy bottom may have a considerably smaller one. It is evident that R may also include any other factor which makes the reflected wave have a smaller amplitude, such as directionality of the source or of the receiver.

It may also be noted that the frequency spacing Δf between successive maxima or minima is given by

$$\Delta f = \frac{c}{\Delta L} \tag{6}$$

where ΔL is the difference in path length of the direct and reflected waves, its value in the above case being $\left(\sqrt{d^2 + 4h^2} - d\right)$.

The partial elimination of reflection interference in test results can be accomplished by (1) reducing the effective value of R by the use of directional sources, screens, etc., (2) averaging out the interference effects through the use of warbled frequency or other multi-frequency signals, (3) making use of pulses which are measured before reflected pulses reach the point of observation, and (4) mathematically eliminating the effects of reflection from the results. Each of these methods has some advantages and some disadvantages which are discussed in detail in the sections following.

5.3.2 Directional Sources

The simplest and one of the most effective methods of eliminating any significant reflections in calibration tests is by the use of directional sources. These must be so designed and oriented that very little acoustic energy reaches the surface or bottom in the direction in which direct specular reflection from the surface or bottom to the position of the receiver occurs. Sources with various types of directivity patterns may be employed, but, for practical considerations, only three require attention: the dipole source, the circular piston source, and the line source.

If the reflecting surface is assumed to be a perfect reflector, and if the directivity pattern of the source is given by $I(\theta)/I_0$ where $I(\theta)$ is the intensity produced at a given distance in a direction making an angle θ with the axis of the source (assumed to be along the line joining the source and receiver) and I_0 is the intensity produced at the same distance on the axis, then R^2 in equation (5) may be put equal to

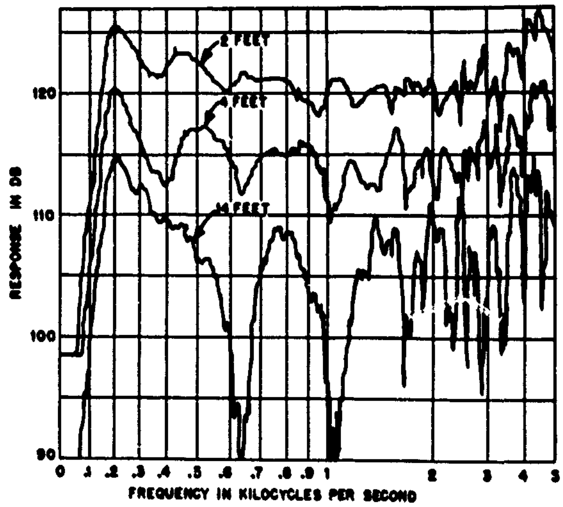

FIGURE 2. Effect of testing distance on response of 3A-32 pressure hydrophone measured with 1J-4 projector. Testing depth = 9 ft. Water depth = 14 ft. Testing distance as shown on curves.

$I(\theta_r)/I_0$ where θ_r is the angle indicated in Figure 3. Now θ_r is given by

$$\theta_r = \tan^{-1}\frac{2h}{d}, \tag{7}$$

so that

$$R^2 = I\left(\tan^{-1}\frac{2h}{d}\right)/I_0. \tag{8}$$

For a dipole source with axis along the line joining source and receiver

$$\frac{I(\theta)}{I_0} = \cos^2\theta, \tag{9}$$

so that (using subscripts to indicate the type of source),

$$\begin{aligned} R_d^2 &= \cos^2\left(\tan^{-1}\frac{2h}{d}\right) \\ &= \frac{d^2}{d^2 + 4h^2} = 1 - \frac{4h^2}{d^2 + 4h^2}. \end{aligned} \tag{10}$$

For a circular piston with axis along the line joining source and receiver,

$$\frac{I(\theta)}{I_0} = \left[\frac{2J_1\left(\frac{\pi D}{\lambda}\sin\theta\right)}{\frac{\pi D}{\lambda}\sin\theta}\right]^2 \tag{11}$$

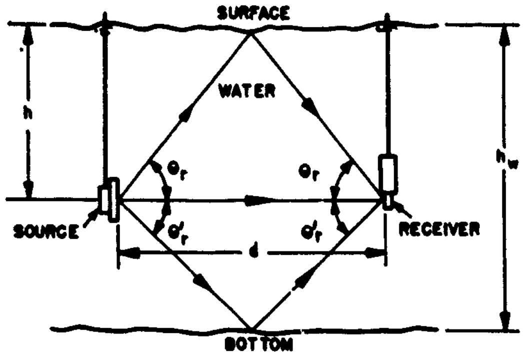

FIGURE 3. Geometry of reflection interference in calibration tests.

with the result that

$$R_p^2 = \left[\frac{2J_1\left(\frac{\pi D}{\lambda}\sin\left\{\tan^{-1}\frac{2h}{d}\right\}\right)}{\frac{\pi D}{\lambda}\sin\left\{\tan^{-1}\frac{2h}{d}\right\}}\right]^2$$

$$= \left[\frac{2J_1\left(\frac{\pi D}{\lambda}\cdot\frac{2h}{\sqrt{d^2+4h^2}}\right)}{\frac{\pi D}{\lambda}\cdot\frac{2h}{\sqrt{d^2+4h^2}}}\right]^2. \qquad (12)$$

The term D is the diameter of the piston, λ the wave length, and $J_1(x)$ the Bessel function of unit order. For a line source of length L suspended vertically,

$$\frac{I(\theta)}{I_0} = \left[\frac{\sin\left(\frac{\pi L}{\lambda}\sin\theta\right)}{\frac{\pi L}{\lambda}\sin\theta}\right]^2, \qquad (13)$$

so that

$$R_l^2 = \left[\frac{\sin\left(\frac{\pi L}{\lambda}\cdot\frac{2h}{\sqrt{d^2+4h^2}}\right)}{\frac{\pi L}{\lambda}\cdot\frac{2h}{\sqrt{d^2+4h^2}}}\right]^2. \qquad (14)$$

Since the side lobes for a circular piston and for a line are of minor importance in the consideration of reflections, R_d, R_p, and R_l may be given approximately (provided h/d is not too large) by the expressions

$$R_d^2 = 1 - \left(\frac{4h^2}{d^2+4h^2}\right), \qquad (10)$$

$$R_p^2 = 1 - \frac{1}{4}\left(\frac{\pi D}{\lambda}\right)^2\left(\frac{4h^2}{d^2+4h^2}\right), \text{ and} \qquad (15)$$

$$R_l^2 = 1 - \frac{1}{3}\left(\frac{\pi L}{\lambda}\right)^2\left(\frac{4h^2}{d^2+4h^2}\right). \qquad (16)$$

The reflected intensity reaching the receiver versus the intensity of the direct wave is then given in db by

$$10\log\left[\frac{d^2}{d^2+4h^2}\left(1 - \alpha\frac{4h^2}{d^2+4h^2}\right)\right], \qquad (17)$$

where $\alpha = 1$ for a pressure-gradient receiver, $\alpha = \frac{1}{4}(\pi D/\lambda)^2$ for a circular piston, and $\alpha = \frac{1}{3}(\pi L/\lambda)^2$ for a line. This equation is plotted in Figure 4. It is seen that, for reducing the effect of reflections, a piston is more satisfactory than a line whose length is equal to the diameter of the piston. At low frequencies, however, where λ becomes large, both a line

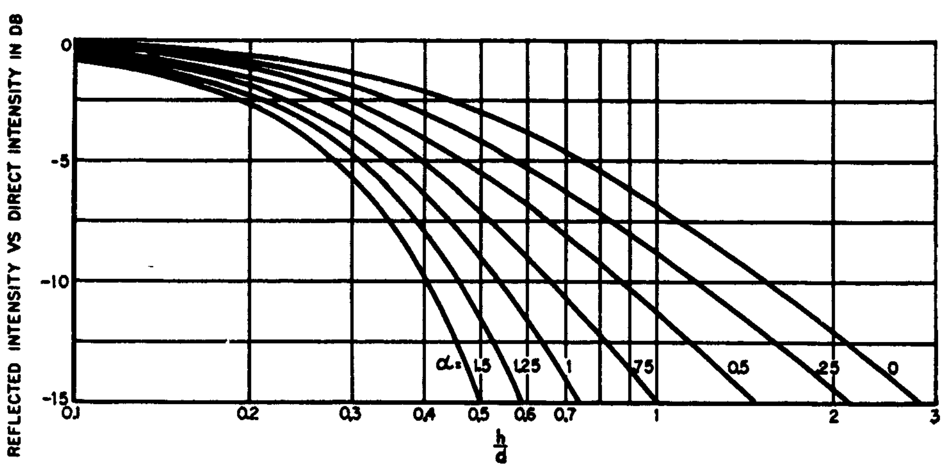

FIGURE 4. Surface reflected intensity versus direct intensity for directional sources. h = depth, d = testing distance. For dipole source $\alpha = 1$; for circular piston source $\alpha = \frac{1}{4}(\pi D/\lambda)^2$, D = diameter of piston, λ = wave length; for line source suspended vertically, $\alpha \doteq \frac{1}{3}(\pi L/\lambda)^2$, L = length of line.

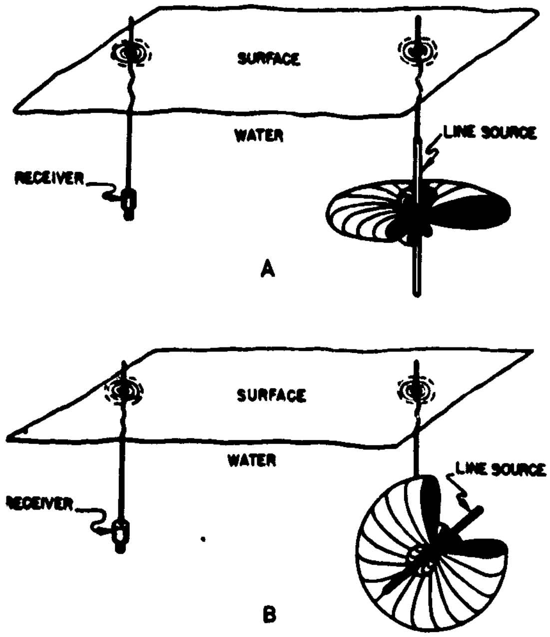

FIGURE 5. Effect of orientation of line source on magnitude of surface reflections.

and a piston become ineffective, but a dipole, whose pattern is independent of the frequency, retains its effectiveness. However, the dipole is inferior to a piston or a line at high frequencies.

At high frequencies, a piston is the most effective source for eliminating interfering reflections. However, before final conclusions as to its usefulness can be drawn, account must be taken of the fact that at relatively close distances the sound field of a piston, even in the absence of reflecting surfaces, is not a free progressive plane wave. This limits the minimum value of the testing distance that may be used. Similar considerations apply to other sources. A discussion of the choice of both testing distance and source will be taken up in Section 5.4 when reflections and so-called proximity effects will be considered.

Another fact should be pointed out. It is difficult to construct a dipole source which develops an appreciable radiation field. This is a result of the fact that the radiation impedance of a dipole source is largely reactive, so that the pressure and particle velocity in the field are almost in quadrature at short distances from the source, and therefore little energy is radiated.

Finally, the characteristics of the receiver must be weighed in considering the elimination of reflections. It has been assumed that the receiver in the preceding discussion was essentially a pressure-sensitive device. Some receivers are essentially velocity or pressure-gradient actuated. The problem is somewhat simplified here, since the velocity components of the reflected wave are not parallel to the axis of the receiver when it is oriented toward the source. Such receivers thus discriminate against surface reflections. However, most receivers have more complex behavior and their discrimination against surface reflections can be judged by their directional patterns. Proximity effects in the receiver are also a consideration limiting the shortness of testing distances. Thus the effectiveness of directional sources in discriminating against surface reflections can be properly judged only when considered with other limitations on testing distances At this point one can only point out the potential value of directional sources in testing.

5.3.3 The Choice of Instrument Orientation

The preceding discussion regarding the use of directional sources to reduce reflections suggests that the choice of orientation of the instruments being tested may make a difference in the prominence of reflection interference. When the instruments have their own directional characteristics, these often can be used to advantage. One prominent example is shown in measuring the frequency response of a line. The directionality of a line hydrophone is such that most of the acoustic energy is contained in the region between two cones having a common vertex and axis, the latter coincident with the line itself. The pattern is roughly like a pancake. If the line is suspended horizontally, the acoustic power incident on the hydrophone from the point on the surface from which reflections are received generates nearly as much voltage as the acoustic energy coming directly from the source (if the latter is nondirectional), as is shown in Figure 5A. However, if the line is suspended vertically, this is no longer the case, for the hydrophone is then relatively insensitive to signals coming from the surface. (See Figure 5B.) Thus considerable reduction in reflection interference can be effected by choosing the vertical orientation for the line rather than the horizontal one. Unfortunately, it is not usually possible to use the same scheme when directivity patterns for the line are being measured.

A second important case occurs in connection with the measurement of the rear response of a projector

or hydrophone, when the receiving directivity pattern is being obtained. If the transmitter is a directional one, it should be so oriented that the principal part of its acoustic energy is directed away from shore. If the projector is oriented in the opposite direction, a large part of the energy is reflected from shore and reaches the receiver coming from that direction. When the receiver is oriented to measure rear response, it is most sensitive to sound arriving from shore. In such a case, the reflected signal voltage may greatly exceed the direct signal voltage. With the other orientation this difficulty is avoided. This is shown quite clearly in Figure 6.

Another scheme which often may be of value in calibrating a source is to use a velocity or pressure-gradient sensitive receiver. Such a receiver is theoretically insensitive to signals coming in from a direction at right angles to its axis. By orienting the source and receiver as shown in Figure 7, the receiver may be made almost entirely insensitive to reflected signals from the surface. The difficulties of rigging the instruments in the proper orientations as shown have essentially prevented this method from being used by USRL.

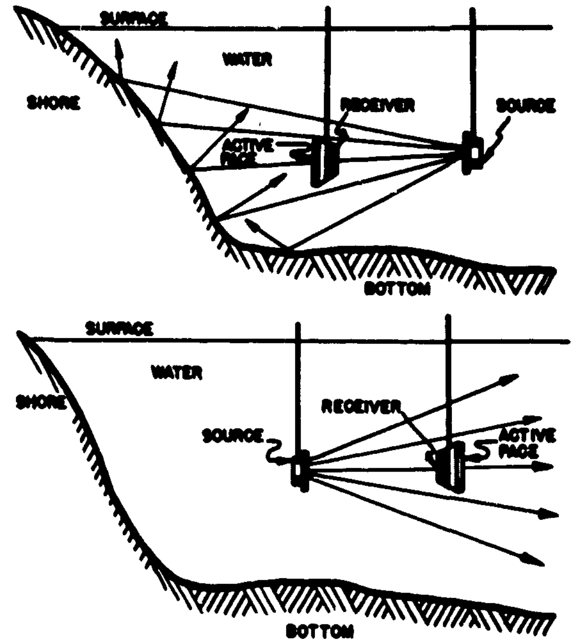

FIGURE 6. Dependence of interference from shore reflections on arrangement of instruments in measuring rear response.

5.3.4 Use of Screens, Lenses, and Orifices

Another method of eliminating reflections which readily suggests itself is the use of screens or baffles to shield the receiver from any but the direct waves from the source, much as is done in optics for similar reasons. This method is not as effective as first thought might indicate because the acoustic wave lengths in which one is interested are generally of the same order of magnitude as the dimensions of suitable baffles, unlike the corresponding situation in optics. Therefore, in the range of frequencies of usual interest, geometrical acoustics is a far from valid representation of acoustic phenomena. However, in spite of the importance of diffraction in such cases, some useful results are obtainable by the proper use of screens or baffles.

The collimation of light by lenses or pinholes is a well-known optical method for preventing stray reflected light from interfering with a measurement. Would it then be possible to use the same methods in acoustics? Consider first the analogue of a pinhole, that is, a large screen in which an orifice is cut, and the source and receiver placed on opposite sides. (See Figure 8.) If the source is placed far enough behind the screen so that the waves reaching the orifice are essentially plane, it is found by a calculation using the wave equation that the resultant sound field on the receiver side of the screen is the same as though the orifice were considered a piston source of the same diameter. The same considerations apply to such orifices as to directional sources of the piston type which have been discussed in the previous section. One is again limited by proximity effects if the receiver is put too close to the orifice. On the other hand, the beam through the orifice has a finite angular divergence and strikes the water surface and is

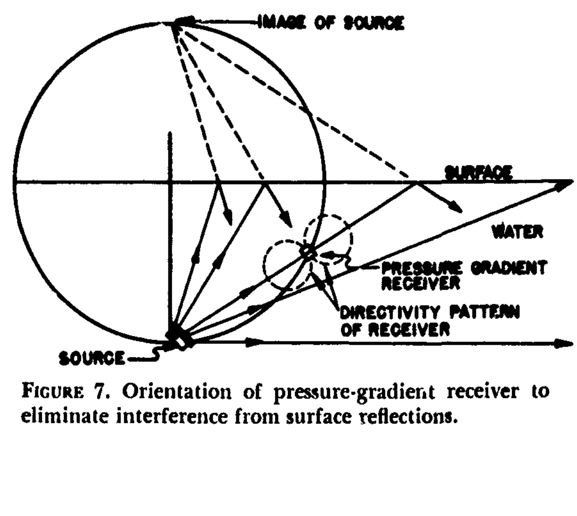

FIGURE 7. Orientation of pressure-gradient receiver to eliminate interference from surface reflections.

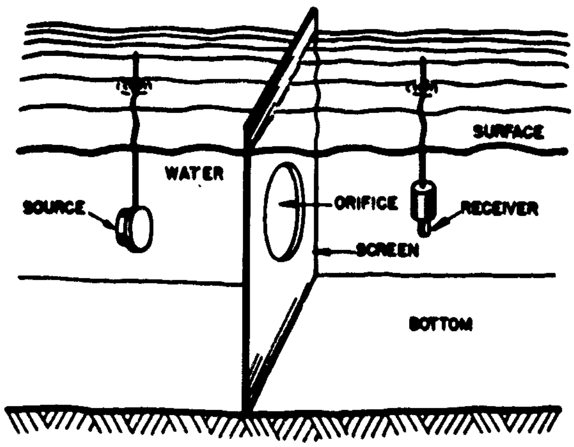

FIGURE 8. Use of screen with orifice to reduce surface and bottom reflections in calibration.

reflected to the receiver again, if the latter is placed too far away. Finally, one cannot place the source too close to the orifice or else the transmitted beam will have too great an angular divergence and thus strike the surface near enough to give a reflected wave to the receiver. Therefore, an orifice in a screen can be considered only as a method of producing an effective piston source of larger area than would be practical for the diaphragm of a projector.

A similar analysis of the feasibility of using acoustic lenses leads to the same conclusions: a lens also acts in principle like a piston source of the same diameter. The construction of suitable acoustic lenses involves various technical difficulties in addition to the theoretical ones outlined above.

A helpful yet considerably simpler method for reducing reflections is by using, at the surface or bottom, baffles or screens so oriented as to cause reflections to be directed away from the receiver. Such screens may be considered to reduce the effective value of the reflection coefficient R. While they may be placed so that, according to geometrical acoustics, no reflected sound should reach the receiver, diffraction about the screen and waves on the water surface usually allow still a considerable part of the reflected sound to reach the receiver. For a given size reflector, the diffraction is greater at lower frequencies. This is unfortunate since the low-frequency region is just the region in which directional projectors also become difficult to construct.

The type of screen used by USRL is essentially a watertight sandwich of $\frac{1}{4}$-inch hard green felt enclosed between $\frac{1}{32}$-inch galvanized iron sheets, and having dimensions roughly 2x4 feet. The layer of enclosed air acts as an effective reflector, and the felt is intended to damp out resonant frequencies.[17]

Two arrangements of screens have been employed. One consists of hanging the screen vertically with the top edge just breaking the surface midway between the source and receiver, with the plane of the screen perpendicular to the line joining the two instruments. (See Figure 9A.) A more effective arrangement has been found to be a pair of screens in the form of a "V" suspended at the surface in the position shown in Figure 9B. In this arrangement, sound reflected from the screen is thrown off more or less sidewise along the surface. A series of such screens placed end to end along the entire distance between source and receiver (Figure 9C) is still more effective. While

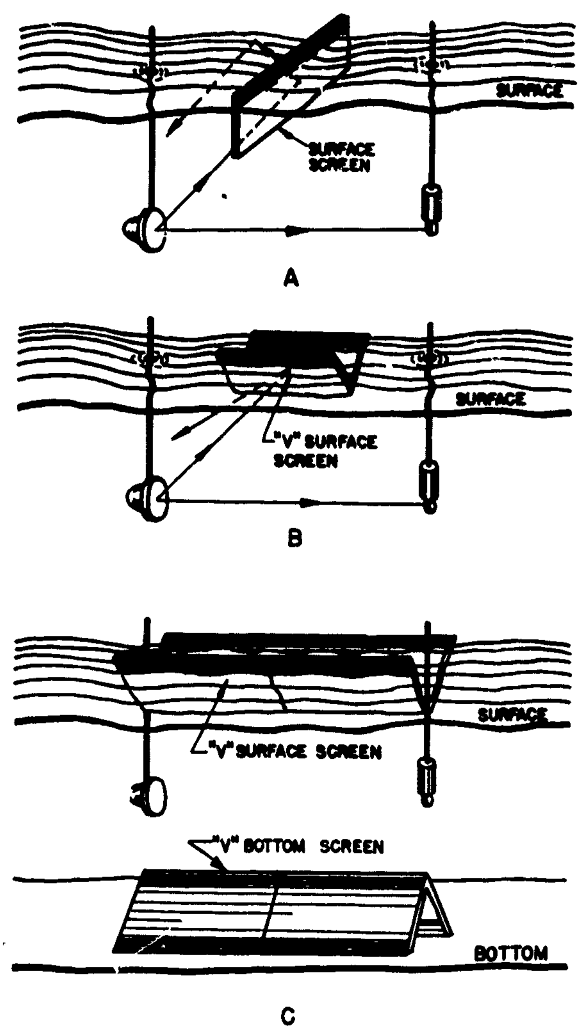

FIGURE 9. Use of screens to reduce surface and bottom reflections.

the effectiveness varies with frequency, at high frequencies, where diffraction is less important, such an arrangement of screens may reduce the effective reflection coefficient R by a factor of from $\frac{1}{10}$ to $\frac{1}{2}$. The ease of construction and handling makes it profitable to have such screens available for use. They may also be used in an inverted "V" arrangement on the bottom to reduce bottom reflections.

It would probably increase the effectiveness of a screen to make it absorbing rather than perfectly reflecting. However, until recently no suitable sound-absorbing materials for underwater use have been available, and it is not yet known how effective these may be.

5.3.5 Electric Signal Methods: Thermal Noise, Warble

There are several methods of reducing the effect of reflection interference which have been used with considerable success in air acoustics. These are based on the fact that the cosine term in equation (3) is a function of frequency, so that, if the response is averaged over a band of frequencies, the oscillatory effect of this term on the response, as the frequency is varied, can be largely averaged out. Two methods of doing this are by using a frequency which is warbled about the frequency at which the response is desired, and by using a band of thermal noise centered at the frequency at which the response is desired. The response as measured by each of these methods is an average over a band of frequencies of the response of the instrument. The fact that a band of frequencies rather than a single frequency is used limits the resolution in response of the instrument. Rapid changes in response become more gradual as measured by this method.

It may be shown that a signal which is warbled between frequencies $f_0 - \Delta f/2$ and $f_0 + \Delta f/2$, with a warbling rate very much less than f_0, has frequencies in its harmonic (Fourier) analysis covering essentially the same frequency range as does the warbling. Similarly, a band of noise of frequency breadth Δf centered at f_0 also contains, by definition, frequencies in this same band. It can be shown mathematically that, to eliminate the effect of interference oscillations in response by either of these methods, Δf must be determined by the inequality

$$\Delta f > \frac{c}{\Delta L} \tag{18}$$

where ΔL is the shortest difference in path between the direct signal and any of the reflected signals.[72]

The extent to which one is interested in resolving the frequency variations in response of an instrument depends to a large extent on the type of instrument being tested. The resolution attained in a method of measurement of the response is defined in the following manner: Consider an instrument which has two very sharp response peaks at frequencies $f - \Delta f/2$ and $f + \Delta f/2$. A method of measurement which is just able to resolve the response into two maxima is said to have a resolving power at the frequency f equal to

$$RP = \frac{f}{\Delta f}. \tag{19}$$

Therefore, the higher the resolving power, the greater the definition with which the method can measure a frequency response. For the average testing program, it is usually satisfactory if the resolving power is equal to 100 or 200 at all frequencies. For the use of warble or noise, the resolving power is

$$RP = \frac{f}{\Delta f} < \frac{f}{\dfrac{c}{\Delta L}} = \frac{f\Delta L}{c}. \tag{20}$$

Hence, for any fixed frequency, the resolving power is determined by ΔL. This limits seriously the use of the method at low frequencies, since, with ΔL fixed as it is by the geometry of the test, the resolving power decreases as the frequency is lowered. Thus for $\Delta L = 5$ feet, the maximum resolving power becomes 100 at 100 kc, 10 at 10 kc, 1 at 1 kc. For rough measurements 10 might be admissible, but any lower values for the resolving power would give very little information of importance. Thus, it is only at high frequencies that the method is of much value.

These methods have another serious disadvantage. After the oscillatory interference terms are eliminated in the expression for the pressure, the pressure that is measured is approximately the square root of the sum of the squares of the pressures in the direct wave and in all of the reflected waves reaching the receiver. Thus, the measured pressure is always greater than the pressure in the direct wave alone. In some cases, such as the measurement of directivity patterns, the reflected waves are often higher in level than the direct wave, so that in this case the direct wave is actually discriminated against by these methods. There-

fore they can be considered useful only in establishing the general shape of the frequency-response curve but not in establishing its absolute level. Even the shape may be in considerable error. The greatest care is therefore required in using these methods to be sure that one is actually measuring the quantity desired.

5.3.6 Electric Signal Methods: Pulses

A more satisfactory method of eliminating the effects of reflected waves in measurements is by the use of pulses. Instead of a steady signal, a pulse corresponding to a sinusoidal signal of finite duration is emitted. This pulse reaches the receiver by the direct path before the reflected pulses arrive. If the response of the receiver can be measured in the interval before their arrival, their effect is entirely eliminated. Since the front of the earliest reflected pulse arrives at a time $\Delta L/c$ after the beginning of the direct pulse, the response measurement must be completed in a time $\tau_m < \Delta L/c$ after the arrival of the beginning of the direct pulse, where ΔL is the smallest difference in path between a direct and reflected signal. It is noted immediately that the pulse method has an important advantage over the warbled-signal and noise-band methods in that the reflected waves play no part in the measurement of response, whereas in the latter methods a composite sum of the direct and reflected signals is measured.

The limitations of the pulse method are indicated by the resolving power of the method. The Fourier spectrum of a pulse of finite length Δt can be shown to contain, essentially, frequencies covering a band of width

$$\Delta f \simeq \frac{1}{\Delta t} \tag{21}$$

centered at the signal frequency of the pulse. The resolving power thus becomes

$$RP = \frac{f}{\Delta f} \simeq f\Delta t \tag{22}$$

which, it would appear, could be indefinitely increased by extending the duration of the pulse. This is illusory, however, since what is measured at a time $\tau_m < \Delta L/c$ must be independent of how long the pulse continues after the period $\Delta L/c$ has elapsed. One would perhaps guess that the actual resolving power would be that corresponding to a pulse duration of τ_m or

$$RP = f\tau_m \leqslant \frac{f\Delta L}{c}. \tag{23}$$

That this is actually the case will be shown now from other considerations.

When a sinusoidal signal is applied to any electrical circuit containing inductances or capacitances or both, steady values of the currents and voltages are not immediately attained. At first there are present, in addition to the steady-state voltages and currents, transient voltages and currents which gradually die out with time. The time required for the transient essentially to disappear is known as the time constant of the circuit. For simple circuits this time constant τ is independent of frequency, but for more complicated ones this may not be the case. For example, for a capacity C and a resistance R in series or *parallel*

$$\tau = RC.$$

For an inductance L and a resistance R in series or parallel

$$\tau = \frac{L}{R}.$$

For a resonant circuit containing an inductance L, a capacitance C, and a resistance R

$$\tau = \frac{2L}{R}$$

when

$$\frac{1}{LC} > \frac{R^2}{4L^2},$$

and

$$\tau = \frac{1}{\dfrac{R}{2L} - \sqrt{\dfrac{R^2}{4L^2} - \dfrac{1}{LC}}}$$

when

$$\frac{1}{LC} < \frac{R^2}{4L^2}.$$

For simple resonant circuits it is convenient to introduce a quantity $Q = 2\pi f_0 L/R$, where f_0 is the resonant frequency. Q essentially measures the number of cycles at resonance required for the transient to die

out effectively. It is also equal to $f_0/\Delta f_0$, where Δf_0 is the difference between the two frequencies, one on each side of resonance, where the current falls to $1/\sqrt{2}$ times its value at resonance. Thus, one may consider it a measure of how peaked the response curve is and, therefore, a measure of how rapidly the current response varies with frequency. For more complicated circuits one cannot define an unambiguous Q, but may often speak of an effective Q, valid for some frequency range, such that Q measures the number of cycles required for the transient to die out. Associated with it is an effective time constant for the circuit τ which is approximately related to Q by the relation $Q = \pi f_0 \tau$.

A transducer has many similarities to an electric circuit, and its response to a suddenly impressed signal can be judged by an effective time constant, or Q, for the transducer. In order to measure the steady-state response of a transducer, one must therefore wait a time considerably greater than τ after the initiation of the signal, say τ_m. Its value must be at least that expressed by

$$\tau_m > \pi\tau. \tag{24}$$

To delineate carefully the response peak of a resonant transducer, one must have a resolving power greater than the ratio of resonant frequency to the breadth of the resonance peak, that is

$$RP > \frac{f_0}{\Delta f_0} = Q \simeq \pi f_0 \tau. \tag{25}$$

Thus, we see that if we set the resolving power equal to $f_0\tau_m$, as we conjectured earlier should be the case, we again get the condition $\tau_m > \pi\tau$, which is in agreement with the result obtained from the consideration of time constants.

It then follows from the condition

$$RP \leqslant \frac{f\Delta L}{c} \tag{26}$$

that the resolving power is limited in the same way as for warbled frequency or noise band signals, thus showing that pulses are likewise ineffective at low frequencies. A general criterion for the usefulness of pulses in obtaining the response of a resonant transducer is

$$(RP)_{\max} = \frac{f_0 \Delta L}{c} > Q = \frac{f_0}{\Delta f_0} \tag{27}$$

or

$$\Delta L > \frac{c}{\Delta f_0} = \frac{Qc}{f_0}. \tag{28}$$

The problem of determining the time constant of a transducer is not an elementary one in itself. In many cases one can determine it *a posteriori* for a resonant device, using the resultant Q obtained from the response curve by a pulse method. If this Q is not less than $\pi f_0 \tau_m$, there will be considerable doubt that the resolving power is greater than the Q. By viewing the received pulses of the transducer on a cathode-ray oscilloscope, one can usually obtain a fair estimate of the time constant. It should be pointed out that a transducer, in contrast to an electric circuit, has its time constant determined not only by its electrical and mechanical elements but also by its acoustic geometry. In order for the local sound field surrounding the transducer to build up to its steady-state value, one must allow sufficient time for the sound waves to pass from one part of the transducer to another and build up the characteristic diffraction pattern about the transducer. The time required for the sound field to reach its local steady-state value is of the order of the linear dimensions of the transducer divided by the velocity of sound. For a long-line hydrophone and even for smaller instruments, the acoustic time constant may be longer than that due to the electrical and mechanical elements. In any case, no response measurement should be made before the acoustic pulse has enveloped the transducer.

The pulsing technique is particularly valuable in measuring directivity patterns, where the reflected signals may be higher in level than the direct signal. This is a case where other available methods often fail (see conclusion of Section 5.3.5).

Methods for producing and measuring pulses are discussed in detail in Chapter 6 along with practical considerations in employing the pulsing technique. The results of pulse measurements on transducers may be found in several reports.[55]

The procedures and problems involved in using the pulsing technique vary with different types of transducers. Careful thought is required before the method is used in any particular case, and preliminary measurements are often helpful in determining its applicability. The preceding discussion should serve as a guide rather than as a rule in making pulse measurements.

5.3.7 Corrections for Reflections

In many tests it is found that the methods of eliminating reflections so far described either are ineffective or, because of the particular nature of the test, cannot be used. In such cases, one must correct the results for the reflections which may have been present during the test. The principal difficulty in mathematically eliminating the effects of reflection interference is the decision as to whether variations in response are a consequence of reflections or are inherent characteristics of the instrument under test. Some useful aids in identifying reflection interferences are the following:

1. If response measurements are made at different testing distances, the difference in path length between the direct and reflected waves is not the same. As a result, the interference maxima and minima in the different response curves appear in different positions. Since variations in the inherent response characteristic of the instrument under test are not shifted by changing the testing distance, this forms a valuable criterion for identifying reflection interferences.

2. It was pointed out in Section 5.3.1 that reflection maxima or minima are spaced regularly with frequency. This spacing between successive maxima or minima is

$$\Delta f = \frac{c}{\Delta L}, \tag{6}$$

where c is the velocity of sound and ΔL is the difference in path between direct and reflected waves. Thus, a periodicity of response maxima or minima with frequency is often indicative of reflection interference and, with the geometry of the test known, one can calculate the frequency spacing by equation (6) to determine whether or not it coincides with the observed values. If there is more than one prominent reflection entering into the test, however, this criterion becomes difficult to apply, since there are maxima and minima introduced by interference between the direct waves and each reflected wave and between the various reflected waves themselves. The resultant effect on the response is quite confusing and makes it difficult to determine unambiguously whether variations are due to reflection interference or are characteristic of the instrument.

3. In calibrating sound sources, two receivers with different directivity patterns may be used. In such cases, reflection interferences have different magnitudes or positions in the two frequency-response curves. This fact is often an aid in deciding whether variations in response are due to reflections or are inherent in the instrument.

Once the reflection maxima and minima have been identified in a response curve, it is necessary to decide how to eliminate them and obtain the inherent response characteristic of the device under test. The most useful method at higher frequencies makes use of the fact that, if the reflection maxima and minima are prominent and the direct and reflected signals do not vary too rapidly with frequency, the maxima appear at frequencies where the direct and reflected signals are in phase, and the minima where they are out of phase. Hence, at a maximum, one measures the sum of the signals in the direct and reflected waves, and at a minimum, their difference. If one takes the signal voltages at a maximum and at an adjacent minimum, the arithmetic mean of these two values gives approximately the correct value.

Probably the best way to make use of this principle is the following: Find the difference in level in db between each maximum and its two adjacent minima. Plot each difference against a function $\phi(f)$ of the mean frequency between that at the maximum and that at the minimum. The points may be connected in a smooth curve. Let $D(f)$ be the voltage generated by the hydrophone due to the direct acoustic signal at sound frequency f and $R(f)$, the voltage from the reflected signal. The measured value at a maximum is expressed by $D(f) + R(f)$ and at a minimum by $D(f) - R(f)$. If these are expressed in db from the usual basic level, the equation for the curve becomes

$$\begin{aligned}\phi(f) &= 20 \log [D(f) + R(f)] - 20 \log [D(f) - R(f)] \\ &= 20 \log \left[\frac{D(f) - R(f)}{D(f) + R(f)}\right] \\ &= 20 \log \left[\frac{1 + \dfrac{R(f)}{D(f)}}{1 - \dfrac{R(f)}{D(f)}}\right].\end{aligned} \tag{29}$$

From this equation, $R(f)/D(f)$ can be determined.

To evaluate $D(f)$, which is the quantity desired, make use of the identity

$$\begin{aligned}20 \log D(f) &= 20 \log [D(f) + R(f)] \\ &\quad - 20 \log \left[1 + \frac{R(f)}{D(f)}\right].\end{aligned} \tag{30}$$

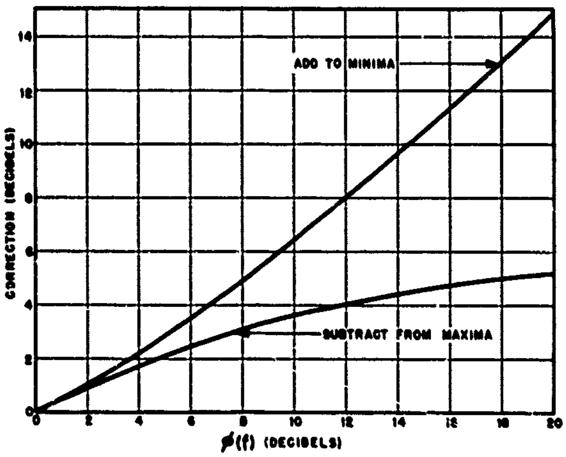

FIGURE 10. Chart for obtaining correct level from difference in level between interference maxima and minima.

The first term is measured directly and the second calculated from the ratio determined above. The true level for the frequency at any maximum is then the measured value minus a determinable correction. By a similar procedure, the correction to be added to the measurement at a minimum is

$$+\,20\log\left[\frac{1}{1-\dfrac{R(f)}{D(f)}}\right]. \tag{31}$$

These corrections are most readily made from the curves of Figure 10 where the subtractive term from (30) and the additive (31) are plotted against $\phi(f)$. Thus, after constructing the maxima-minima difference plot, one need only take the value of $\phi(f)$ corresponding to the frequency of each maximum and, on going to Figure 10, read the number of decibels to be subtracted from the maximum to give the correct level. A similar process gives the number of decibels which should be added to a minimum to find the correct level.

While the above method is very useful in many cases, it is not too satisfactory at low frequencies, since it is difficult then to locate unambiguously the maxima and minima. There is no reasonably good method for correcting for reflections at low frequencies. One method may be of some aid, if only surface reflections are prominent and both the source and receiver are nondirectional. It is based on the fact that under these conditions one can actually calculate the observed pressure at the receiver in terms of the pressure which would be present if the reflecting surface were not present. This procedure can be carried through by following the instructions given with the nomographical chart, Figure 11. This method is useful for calibrating very low frequency projectors.

In the calibration of receivers by the comparison method, the problem is somewhat simplified if the receiver under test and the one serving as a reference standard are either both nondirectional (pressure-activated) or both pressure gradient, since in this case the reference field, even though it contains reflections, is the same for both instruments, and their relative calibration is correct in spite of the presence of reflections.[31]

5.4 CHOICE OF TESTING GEOMETRY

5.4.1 Depth

The testing geometry for a calibration test refers to the testing depth and distance used. The optimum depth is usually determined by the testing site so that in general it remains the same during most tests. This depth is limited by the available water depth and, as a rule, its optimum value is that for which the magnitude of reflections from the surface is equal to that of those from the bottom. If R_s and R_b are the effective pressure reflection coefficients for the surface and the bottom respectively, h_w the depth of the water, h the testing depth, and d the testing distance, then the intensity of the reflected wave from the surface to the receiver is

$$I_s = \frac{R_s^2 I_0 d^2}{d^2 + 4h^2}, \tag{32}$$

where I_0 is the intensity of the direct wave. The intensity of the reflected wave from the bottom is

$$I_b = \frac{R_b^2 I_0 d^2}{d^2 + 4\,(h_w - h)^2}. \tag{33}$$

Placing these equal to express the desired condition and solving, gives

$$\frac{h}{h_w} = \frac{1}{1-\dfrac{R_b^2}{R_s^2}} - \sqrt{\frac{\dfrac{R_b^2}{R_s^2}}{\left(1-\dfrac{R_b^2}{R_s^2}\right)^2} - \frac{d^2}{4h_w^2}}. \tag{34}$$

For d small, this reduces to

$$\frac{h}{h_w} = \frac{1}{\dfrac{1+R_b}{R_s}}. \tag{35}$$

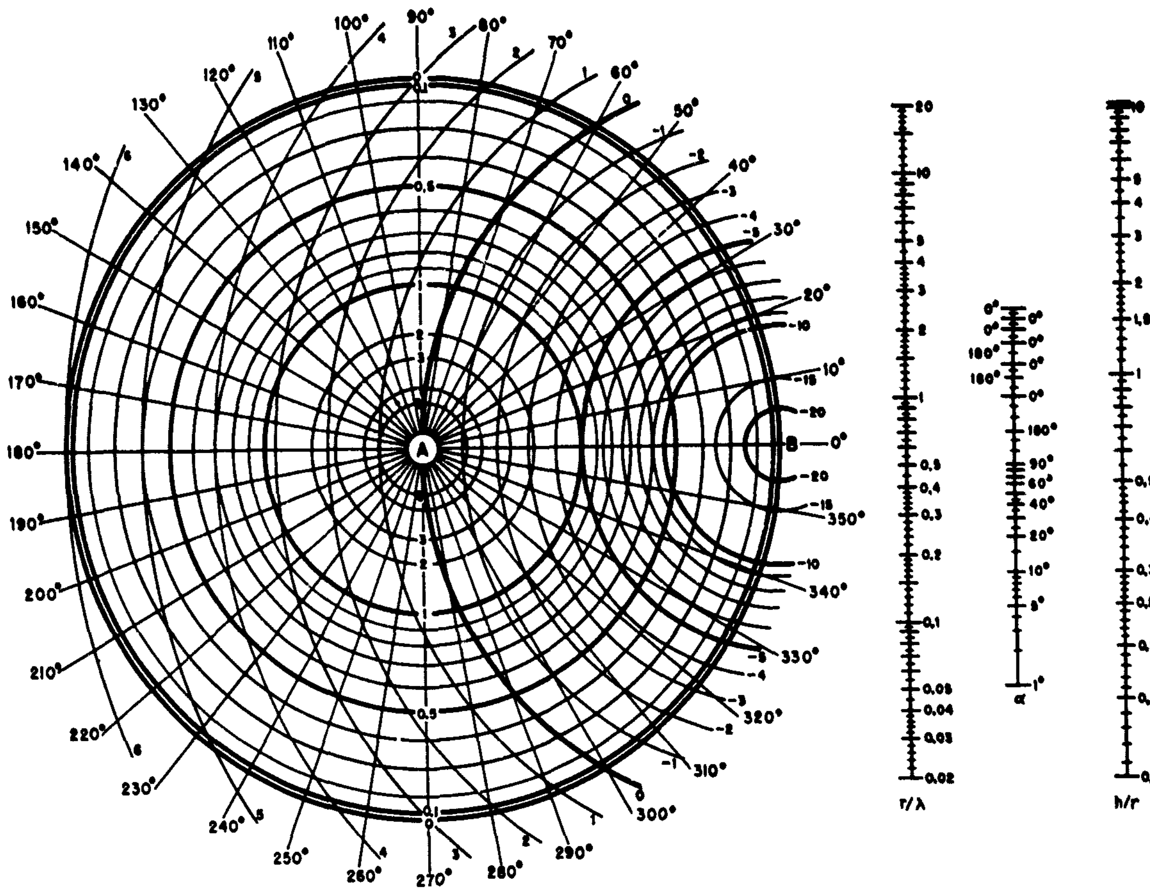

FIGURE 11. Correction chart for surface reflections at low frequencies for nondirectional instruments.

Instructions:

Let h = depth of hydrophone and projector.
r = testing distance.
λ = wave length.
p = RMS pressure at hydrophone with surface present.
p_0 = RMS pressure at hydrophone if surface were not present.

Calculate h/r and r/λ. Proceed to the alignment chart on right and place a straight edge so that it crosses the scale marked h/r at the calculated value and the scale marked r/λ also at the calculated value. Read the angle α at the intersection of the straight edge and the scale marked α. Proceed to the diagram on left. Find the circle with center at A whose indicated value corresponds to the calculated value of h/r. Find the point of intersection of this circle with the radial line corresponding to the value of α previously obtained. Then the value indicated on the circle, with center at B, on which this point lies will be the value of

$$20 \log \frac{p}{p_0}.$$

Interpolate if necessary.

Example. Let $h = 5$ ft, $r = 10$ ft, frequency equals 150 c.

Then
$$\frac{h}{r} = 0.5,$$

$$\lambda = \frac{v}{f} = \frac{4800}{150} = 32 \text{ ft in water,}$$

$$\frac{r}{\lambda} = 0.313.$$

From the alignment chart: $\alpha = 47°$.

From the diagram: $20 \log \frac{p}{p_0} = 2.6$ db.

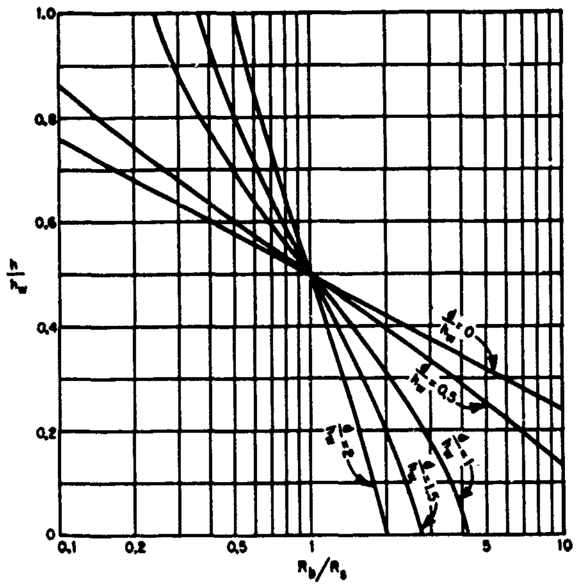

FIGURE 12. Determination of testing depth.

Equation (34) is plotted in Figure 12 for convenient reference. In the above derivation it is assumed that R_b and R_s are independent of the angle of incidence and thus of d and h. However, since these reflection coefficients do depend upon the angle of incidence, and since their effective values depend also on the directivity of the device being tested, equation (35) should serve as a guide rather than as a rule in choosing the testing depth. Usually a testing depth lying between ½ and ¾ of the water depth is satisfactory. The more absorptive the bottom, the greater is the relative testing depth which may be used.

5.4.2 Distance

Choosing the optimum testing distance is even more difficult than choosing the optimum depth, since more considerations must enter into the determination of the former. If the testing distance is too great, reflection interference becomes very prominent, and when a low intensity source is used, difficulties with ambient noise may arise. On the other hand, if the distance is too short, proximity effects due to the spherical wave front incident on the receiver introduce errors into the calibration, or a standing wave diffraction pattern may be set up between transmitter and receiver. Thus, the selection of the optimum distance must be made as a compromise between these competing effects. The dependence of surface reflections on testing distance and depth has been discussed in considerable detail in preceding sections of this chapter. Now it is necessary to discuss the proximity effects in detail before a criterion for the selection of testing distance can be determined. Because of the reciprocity principle (see Chapter 3 and Section 5.5.6), proximity effects for a transducer are the same whether it is acting as a transmitter or as a receiver.

5.4.3 Proximity Effect for Pressure-Gradient Receivers

A pressure-gradient or velocity-type hydrophone is one whose response is (at least over a certain frequency range) proportional either to the component of the pressure gradient or to the particle velocity of the sound field parallel to the axis of the hydrophone, rather than to the pressure in the sound field. In a plane sound wave, the pressure gradient is proportional to the pressure in the sound field, the proportionality constant being independent of frequency. For spherical waves this is not the case except for sufficiently great distances from the center, where the wave front is essentially plane over the hydrophone. Since the calibration of pressure-gradient hydrophones usually is desired in terms of the equivalent plane wave pressure, it is then necessary to employ a spherical wave correction.

To obtain this correction, one uses the equation for the pressure in a spherical wave at a distance r from the center

$$p = \frac{p_0 e^{-jkr}}{r} \tag{36}$$

where p_0 is a constant, and $k = 2\pi/\lambda$, λ being the wave length. The radial component of the pressure gradient is then given by

$$\frac{dp}{dr} = -p_0\frac{(1 + jkr)e^{-jkr}}{r^2}. \tag{37}$$

The ratio of pressure gradient to pressure is therefore given by

$$\frac{\left(\frac{dp}{dr}\right)}{p} = \frac{\left(\frac{-p_0(1 + jkr)e^{-jkr}}{r^2}\right)}{\left(\frac{p_0 e^{-jkr}}{r}\right)} = -\frac{(1 + jkr)}{r}, \tag{38}$$

or its absolute value is

$$\left|\frac{\frac{dp}{dr}}{p}\right| = \left[\frac{1+k^2r^2}{r^2}\right]^{\frac{1}{2}}. \tag{39}$$

Where r is large and the wave front is essentially plane, this ratio becomes simply k. Therefore, if a pressure-gradient hydrophone, calibrated in terms of the equivalent plane-wave pressure, is placed in a spherical sound field at a distance d from its center and with its axis radial, it then indicates a pressure which is greater by the ratio of equation (39) to k, or

$$\left[\frac{1+k^2d^2}{k^2d^2}\right]^{\frac{1}{2}} = \left[1+\frac{\lambda^2}{4\pi^2d^2}\right]^{\frac{1}{2}} \tag{40}$$

times the actual pressure present at its location. Note that d now replaces r in equation (39). Thus, the hydrophone indications should be corrected by this factor to obtain the true pressure. This correction factor in db is plotted in Figure 13 for four values of d. It is to be noted that it is most prominent at low frequencies. The correction factor is to be subtracted from the observed pressure in db to obtain the correct value.

One might conclude from the above that one may work at any testing distance with a pressure-gradient instrument and simply apply the above correction. However, it must be remembered that most transducers do not have a spherical wave field in their immediate neighborhood. This is true in particular for piston-like transducers, where the sound field in the immediate neighborhood of the face of the transducer is very complicated and does not become spherical for what is often a considerable distance from the diaphragm. Consequently, great caution must be used in applying this correction.

5.4.4 Proximity Effect for Pistons: Axial Response

Most acoustic transmitters and receivers are coupled to the acoustic medium by a diaphragm which oscillates in a direction normal to its plane under the influence of the pressure in the sound field when receiving, or under the electromechanical forces of a transducer when transmitting. The sound field of such a piston source of finite area falls off according to the inverse-square law at large distances, where the wave fronts are spherical. Close to the transducer,

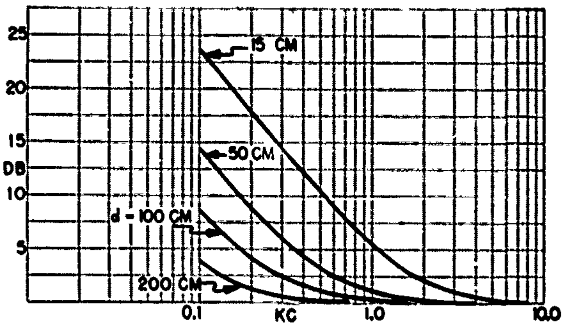

FIGURE 13. Increase in sensitivity of pressure-gradient hydrophone in a spherical sound field.

however, the sound field is very complex and cannot be considered spherical. Only the case of a piston situated in an infinite rigid baffle is amenable to simple theoretical analysis because then there are no edges to cause diffraction. The present discussion is limited to this case. The results may be applied satisfactorily to any piston whose dimensions are not small compared to a wave length.

Consider first the case of a circular piston. The pressure along a line normal to the plane of the circle at its center is, at a distance r from the piston,

$$p = 2\rho c v_0 \left|\sin\frac{k}{2}(\sqrt{a^2+r^2}-r)\right|, \tag{41}$$

where ρ is the density of the medium, c is the sound velocity in the medium, v_0 is the normal velocity of the piston, $k = 2\pi/\lambda$, and a is the radius of the piston.[73] This obviously does not vary inversely with r for small values of r. However, as r becomes large compared to a, the radical may be expanded to obtain

$$p = 2\rho c v_0 \left|\sin\frac{ka^2}{4r}\right|. \tag{42}$$

If $\frac{ka^2}{4r} = \frac{\pi a^2}{2\lambda r} << 1$, the sine function may be expanded to obtain

$$p_0 = \frac{\pi a^2 \rho c v_0}{\lambda r} \tag{43}$$

where p_0 is used to indicate the pressure at distances where

$$r >> \frac{a^2}{\lambda} \text{ and } \frac{r^2}{a^2} >> 1. \tag{44}$$

In this region, the inverse-square law does hold, and the pressure does vary inversely with r.

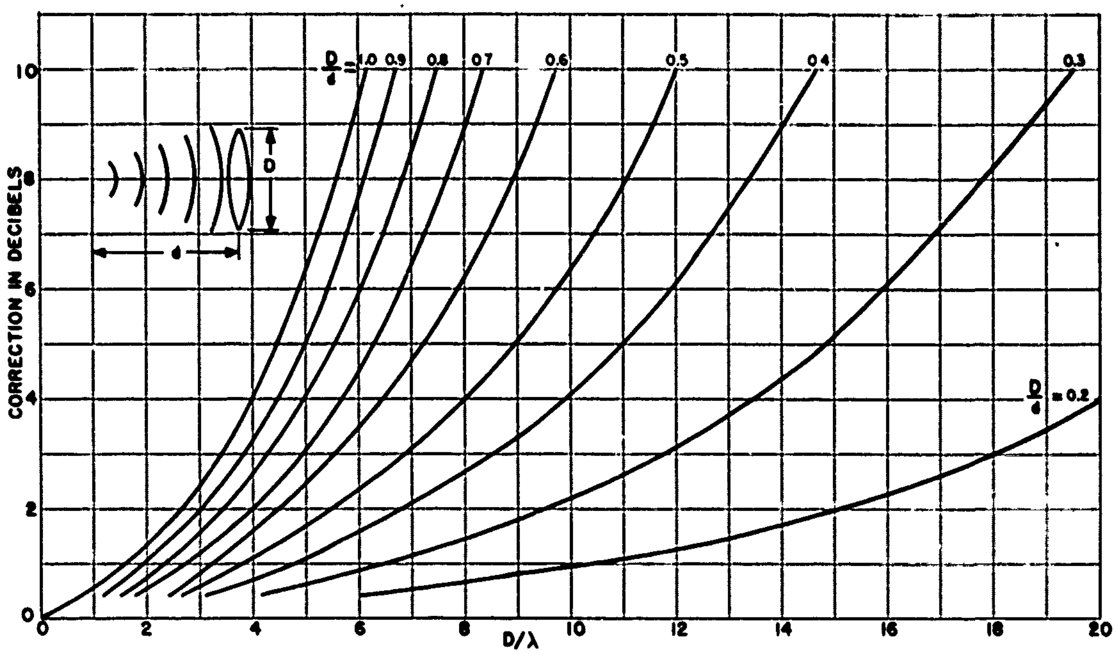

FIGURE 14. Spherical wave correction for circular piston. Correction to be added to measured response.

The deviation from the inverse-square law may be treated as a correction. What one would like to measure is p_0 as given by equation (43). Thus, the ratio of the measured pressure to the desired result is

$$\frac{p}{p_0} = \frac{2\lambda r}{\pi a^2}\left| \sin \frac{k}{2}(\sqrt{a^2 + r^2} - r)\right|. \tag{45}$$

Substituting for r the usual symbol for testing distance d, and for a, ½ the diameter of the piston $D/2$, this equation becomes

$$\frac{p}{p_0} = \frac{8\lambda d}{\pi D^2}\left| \sin \frac{\pi}{\lambda}\left(\sqrt{\frac{D^2}{4} + d^2} - d\right)\right|. \tag{46}$$

A chart is given in Figure 14 showing the corrections in db to be added to the measured values. A similar analysis may be made for a line transducer. The corrections for this instrument are shown in Figure 15 where L, the length of the line, replaces D.

While the preceding derivation is for a circular piston, essentially the same limit holds for a piston of any shape if the diameter of the piston is replaced by a characteristic linear dimension for the shape under consideration. A general criterion for the domain where the inverse-square law is valid for a piston is given by

$$d > \frac{L^2}{\lambda}, \tag{47}$$

and

$$d > 2L \tag{48}$$

where L is the longest dimension of the piston.

5.4.5 Proximity Effect for Pistons: Directivity

The effect of proximity on the directivity pattern of a transducer is not as amenable to calculation as the effect on the axial response. To avoid appreciable effect due to proximity in directivity measurements, the following criteria should essentially be met:

$$d > \frac{L^2}{\lambda}$$

and

$$d > 10L. \tag{49}$$

Qualitatively, the effects on directivity patterns of measuring at a closer distance than prescribed by the above criteria are known. Measurements show that the measured beam width is broader than that found at distances in the inverse-square-law region. The side lobes of the pattern appear higher than those for long distances, and the minima separating the various lobes begin to fill in. These effects are shown for an extreme case in Figure 16, where testing distances

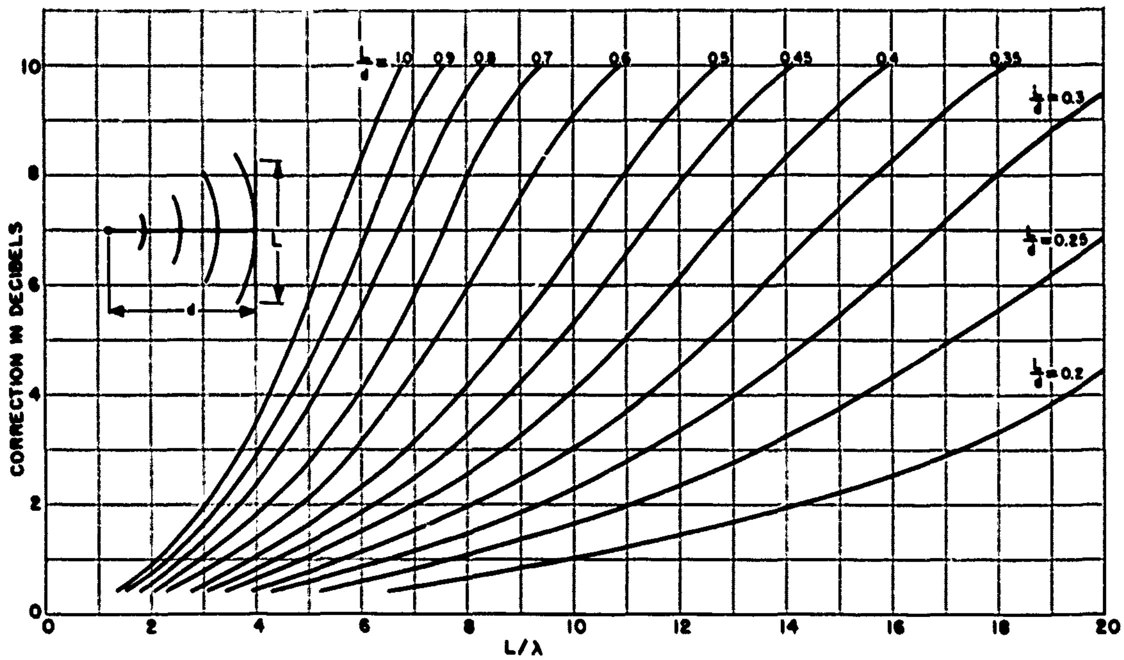

FIGURE 15. Spherical wave correction for a uniform line. Correction to be added to measured response.

of 1.5 feet and 9 feet are compared. The critical distance for the projector tested in this example is about 5 feet.

When measuring axial response, the first criterion, $d > L^2/\lambda$, is the more important practical one, but for directivity patterns the second criterion, $d > 10L$, is about equally important. This results from the fact that the directivity pattern of a device is due largely to cancellation at certain angles of in-phase and out-of-phase pressures on the active surface. Close in, the inverse-square-law effect makes the amplitude smaller on the more distant parts of the transducer, so that cancellation is not so effective. This effect is particularly troublesome for a long-line hydrophone, since the testing distance must be very great to keep the amplitude at the two ends of the line approximately equal when the line has a radial orientation with respect to the source or receiver.

5.4.6 Other Proximity Effects

Another proximity effect which occurs with directional transducers is connected with their beam patterns. If the beam pattern of one is quite sharp, it may allow an appreciable variation of amplitude over the face of the other, independent of the inverse-square-law effect. When a directional source is used, the variation in pressure over the area of the opposing transducer should certainly be less than 1 db if the proper response is to be obtained.

When two transducers face each other during a test, the sound field at the receiver includes the doubly diffracted (or reflected) field produced by the original wave from the source being diffracted by the receiver and then rediffracted by the source back to the receiver. This effect is usually negligible, except when two transducers of large area oppose each other at a short distance, in which case a severe standing wave pattern may be set up between them. The standing waves may even be of sufficient magnitude to change the apparent acoustic impedance of the medium as viewed by the source. While this factor is rarely a cause of trouble, it should be kept in mind when working with transducers of large area.

Finally, it should be remembered that in a test the proximity effects for both instruments must be considered and allowance made for the nature of each in selecting the testing distance.

5.4.7 Correction for Proximity Effects

The fact that the error due to a spherical wave front can be calculated for many commonly occurring cases, such as the pressure-gradient transducer, the circular piston, and the line, suggests that corrections can be made for this effect. Such is indeed the

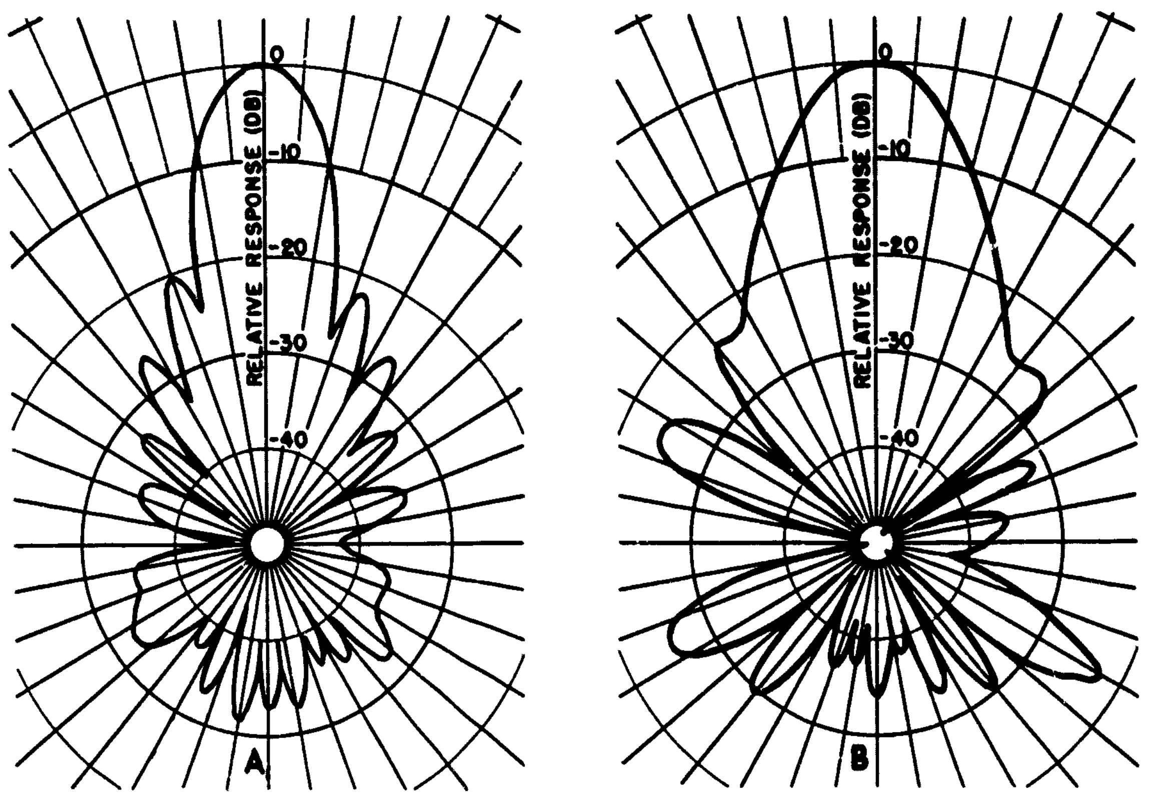

FIGURE 16. Effect of testing distance on directivity pattern. (A) testing distance = 9 ft, (B) testing distance = 1.5 ft. For this transducer $L^2/\lambda = 5$ ft.

case but, as in all other cases where corrections are applied, caution is necessary. The calculations are carried out on the basis of the transducer's behaving in a certain well-defined manner. For example, it is assumed that all parts of a piston move with the same velocity and in the same phase. Actual instruments only approximate this behavior and in many cases depart significantly from it. The amplitude of a piston is often smaller at the edge than at the center, or the piston may actually break up into areas which oscillate out of phase. Instead of having uniform sensitivity, lines are often made up of an array of discrete elements and are often *shaded* or *tapered,* that is, have intentionally reduced sensitivity at the ends in order to suppress side lobes. The validity of the theoretical formulas is then questionable.

One must conclude, as a general rule, that a theoretical correction of more than 5 db is open to considerable question, even if all other criteria as to applicability of the theoretical correction are favorable. If possible, test conditions should be selected so that corrections for spherical wave effects are avoided. When corrections must be made, the charts in Figures 13, 14, and 15 giving the corrections for a pressure-gradient device, a circular piston, and a line will be found useful.

5.4.8 Summary of Testing Geometry

The important factors which determine the testing geometry to be used in calibration measurements have now been discussed. It remains to summarize a procedure for selecting the optimum testing distance and testing depth. An outline is given in the following.

1. Select the testing depth. If the reflection coefficient of the bottom is known, Figure 12 may be used. If the coefficient is not known, a testing depth of from ½ to ¾ the water depth is usually satisfactory. If the water is very deep, the greatest depth consistent with satisfactory rigging of the instruments is desirable.

2. If both instruments are nondirectional, as small a testing distance as possible is desirable. It should

not, however, be smaller than several times the largest dimension of either instrument. Surface screens and bottom screens may be helpful in reducing reflections. If the instruments have a relatively flat response, that is, low Q or time constant, pulses may be used to advantage with a possible increase of testing distance.

3. If one of the instruments is a pressure-gradient device and the other nondirectional, and if no spherical wave correction is to be applied, the testing distance should be greater than half a wave length. If a spherical wave correction is to be applied to the results, it should not be greater than 5 db if it is possible to avoid it. This means the testing distance should exceed $\frac{1}{10}$ of a wave length. As a rule reflections are not severe until the testing distance is greater than the depth, and surface screens may increase this distance. This means that reasonably good calibrations can be obtained down to frequencies where the wave length is about ten times the depth.

4. If two pressure-gradient instruments are used, the testing distance should not be less than a wave length, since closer to a transmitter of this type the pressure gradient is no longer radial. If it is necessary to work closer, a correction can be computed and applied to the results.

5. When a directional transducer of the piston type and a nondirectional instrument are used, the testing distance selected should be such that errors due to proximity effects are about equal to errors due to reflection interference. The possible variations in this case are many and depend on the size of the transducer and the frequency, but by an examination of Figures 4 and 14 one usually can reach a reasonable compromise. If possible, the reflected intensity given in Figure 4 should be 10 db or more down. To avoid spherical wave corrections, the testing distance should be larger than D^2/λ. If it is necessary to use shorter distances, a spherical wave correction from Figure 14 may be applied, but any correction greater than 5 db must be considered unreliable. The pulse technique may be of value in such tests.

6. The same considerations given in the preceding paragraph apply to a pressure-gradient instrument facing a directional transducer of the piston type, except that a different spherical wave correction must be applied. The fact that the pressure-gradient instrument has directionality itself reduces reflection interference difficulties. The reflected intensity is below the direct intensity in decibels by the sum of the values obtained for each instrument from Figure 4.

7. When two piston-type transducers face each other, reflection interference is not usually a source of trouble because of the directivity of the transducers, except at very great separations. On the other hand, proximity effects become of greater significance, and the separation should be great enough so that:

a. Spherical wave effects are small. This requires that any testing distance d satisfy the conditions

$$d > \frac{D_1^2}{\lambda} + \frac{D_2^2}{\lambda} + \frac{6D_1D_2}{\lambda},$$

and

$$d > 2D_1$$
$$d > 2D_2, \tag{50}$$

where D_1 and D_2 are the diameters of the two pistons. This also keeps the pressure due to one transducer uniform over the face of the other in spite of the directivity of the instruments.

b. No standing wave pattern is formed between the faces of the two instruments. This generally is taken care of if the criteria in the preceding paragraph are met.

When measuring directivity patterns, the last two conditions of equation (50) should be changed to $d > 10D_1$ and $d > 10D_2$ to avoid the effect of varying pressure due to the inverse-square law.

8. Essentially the same considerations apply to line instruments as apply to piston-type transducers provided one substitutes the length of the line for the diameter of the piston. If the line is suspended vertically, there are ordinarily no great difficulties in obtaining a calibration except possibly at low frequencies. Spherical wave corrections are useful when a testing distance sufficiently great to eliminate proximity effects cannot be used. If a line is suspended horizontally, surface reflection usually causes great difficulty and makes it almost impossible to obtain good directivity patterns except with great testing depths. The inverse-square-law effect also makes it difficult to obtain good directivity patterns except at great distances, which are consequent on great depth. The pulsing technique may be of aid, but it must be remembered that, with the line mounted end-on with respect to the source or receiver, the acoustic time

constant is at least the length of the line divided by the velocity of sound. Unless deep water is available, this time may be greater than the time required for an interfering reflected pulse to appear.

While the outline given above should be of aid in fixing the geometry for a test, it must be remembered that each test has its own particular factors involved and thus no general rule can be made. Experience and judgment are of primary value in making a proper choice. It is nearly always helpful to repeat tests with a changed geometry, particularly when it is suspected that reflections or proximity effects are causing trouble. One then has an internal check on the validity of the corrections that may have been applied, as well as a means of recognizing the presence of interfering reflections or other extraneous effects.

5.5 THE ESTABLISHMENT OF SOUND FIELDS

5.5.1 Absolute and Relative Calibrations

The calibration of underwater sound devices requires reliable knowledge of the magnitude of sound fields in water. Two techniques for establishing these magnitudes may be distinguished. One involves a direct absolute measurement of the field intensity; the other uses previously calibrated instruments either to establish a known sound field or to measure one which is present. Among the available methods of the first type are the Rayleigh disk method, the radiation pressure method, the reciprocity method, and various motional impedance methods. The second technique requires calibrated instruments, whose calibrations have been obtained either by some of the absolute methods mentioned above, or by such methods as computation from their design or calibration in air. In the routine calibration and testing of underwater sound devices, the method of relative calibration with a known standard is far more convenient than a direct absolute calibration, which requires considerable care and is more time-consuming. It has the disadvantage that it is based on the stability of the reference standard, but numbers of these standards have been constructed whose calibration remains sufficiently constant for the accuracy usually desired in relative calibrations. The most satisfactory absolute method in water is the reciprocity method, and it is now exclusively used by USRL for the absolute calibration of standards. In the following sections the various methods of obtaining absolute calibrations are discussed.

5.5.2 Absolute Calibration from Design of Standard

In principle, if the design of a transducer is completely specified, one can theoretically calibrate the device over its entire frequency range by solving the equations of acoustics, mechanics, and electromagnetism involved in its operation. Actually, the equations are too complicated to allow a practical solution unless some assumptions are made. In spite of these approximations, it may often be possible to obtain a reasonably valid theoretical response characteristic for the device over a considerable range of frequencies. This method has been applied with considerable success to certain standards in use at USRL, in particular to the 3A Rochelle salt crystal hydrophone and to the 1A pressure-gradient type hydrophone designed by the Bell Telephone Laboratories.[9,24] The principal difficulties in the method are the following:

1. It is not feasible to take into account all possible modes of vibration of the device and its housing, but only the desired mode and perhaps a few closely-coupled ones. However, some of the neglected modes are excited in operation, particularly near their resonant frequencies, and may introduce "break-ups" in the response which will not be included in the computed calibration.

2. At all frequencies, but particularly at those having wave lengths of the order of magnitude of the dimensions of the device and higher, diffraction around the instrument plays an important role. This diffraction effect is very difficult to compute, and computations have been carried out only in some highly idealized cases. Thus, it is difficult to include in the theoretical calibration precisely the effect of diffraction.

3. Some of the constants of the mechanical elements involved in the construction of an instrument are not easily measurable. In particular, mechanical resistance as a function of frequency as well as of the effective mass and stiffness of various elements may be difficult to obtain over the desired frequency range.

4. The method can be applied only to the relatively few instruments designed with this method of calibration in view, and then only by skilled person-

nel intimately familiar with every phase of the design.

5. The reliability of calibration obtained in this way is always open to question, unless a check can be obtained by other methods.

6. The frequency range which may be covered is limited.

One must conclude, consequently, that this is not a very satisfactory method of absolute calibration, although its principles are essential to the design of satisfactory reference standards.

5.5.3 Absolute Calibration from Calibration in Air

Initially, the technique of calibration of acoustic devices in air was developed considerably beyond that in water. If one could obtain the calibration of a device in water from its calibration in air, one would have a useful method of calibration for underwater sound devices. The mechanical and electrical elements of a transducer are not functions of the medium in which it is immersed. Therefore, it is necessary to consider only the effect of a change of medium on the acoustic elements. The important parameters are the density and the sound velocity. If a device is essentially pressure-actuated, the voltage which it develops in a sound field is proportional to the pressure properly integrated over its surface, including the pressure due to diffraction. At wave lengths where diffraction is negligible for a stiff[d] device, the pressure acting is simply the pressure in the field, so that the acoustic pressure is the same regardless of the medium. Thus, at low frequencies a stiff pressure-actuated transducer has the same receiving response in air and in water. The upper frequency limit for this equality is determined by the frequency at which diffraction becomes important. This frequency is $\frac{1}{4}$ to $\frac{1}{5}$ as high in air as in water because of the 4.3 to 1 ratio of the velocities of sound in the two media. For a device of the order of 1 inch in size, the frequency at which diffraction becomes important is about 12 kc in air and about 60 kc in water. Thus, for a pressure-operated device of this type, such as the 3A hydrophone, a water calibration up to about 10 kc can be obtained from an air calibration, and, by a judicious frequency translation of diffraction effect, the calibration may often be extended higher.

For a pressure-gradient operated instrument, the response is essentially proportional to the pressure gradient in the sound field. Now, for the same frequency and pressure in a plane wave in air and in water, the ratio of the pressure gradient in air to that in water is equal to the ratio of the sound velocity in water to that in air. If this were the only effect, a pressure-gradient transducer would be 20 log 4800/1100 = 12.7 db more sensitive in air than in water at the same frequency. However, in such devices the change in radiation impedance with change of medium is often not negligible. The radiation reactance of the transducer is a function of the density of the medium, and the functional dependence is different for different instruments. This effect must also be taken into account. For the 1A hydrophone, the additional correction amounts to 3.3 db, making the hydrophone 16 db less sensitive in water than in air at the same frequency. In addition, diffraction effects become a factor in the response at different frequencies for the two media, as pointed out above for pressure-type instruments.

Thus, a calibration in air[9,24] can be used to give a calibration in water only over a limited frequency range. The original calibrations of USRL standards before the reciprocity method was adopted were obtained in this fashion.

While, with judicious treatment of the data, these methods can give reasonably good calibrations over the most important part of the frequency spectrum for underwater sound work, they have distinct disadvantages:

1. They are relatively laborious and require for their proper execution intimate knowledge of the instrument, as well as personnel highly skilled in the technique of air calibration and in the principles of acoustic design.

2. They can be applied only to relatively few instruments which are designed with this method of calibration in view.

3. There is no check on their reliability and no positive assurance that the various modes of vibration of the device may not be excited to different degrees in air and in water.

4. Theoretical corrections, whose validity may be questionable, must be applied to the results.

5. The frequency range which may be covered is limited.

[d] By "stiff" is meant that, at the frequencies of interest, the radiation impedance is small compared to the mechanical impedance of the transducer.

5.5.4 Quasi-Static Calibration

For an acoustically stiff pressure-operated instrument at frequencies low enough so that the wave length is long compared to the dimensions of the instrument, the response depends only on the pressure in the neighborhood of the instrument. It is independent of the type of wave giving rise to the pressure, of its direction of propagation, and even of whether there is a wave present at all, so long as a hydrostatic pressure variation of corresponding amplitude and frequency is present. To calibrate such an instrument in this low-frequency register, it is necessary only to produce a known pressure variation in the portion of the medium adjoining the instrument. Several possible methods of calibration are based on this principle.

For frequencies below a few cycles per second, one can bring about this pressure variation in water simply by raising and lowering the device sinusoidally through a known distance at the desired frequency. If the depth in centimeters is h, then the rms pressure in dynes per sq cm acting on the transducer is

$$p = \frac{\rho g h}{2\sqrt{2}} \tag{51}$$

where ρ is the density of water (1 gram per cu cm) and g is the acceleration of gravity (980 cm per sec per sec). If the test is carefully made, accurate calibrations in this low-frequency range can be made.

At higher frequencies, it is possible to use a tank in which the pressure is varied sinusoidally through known values. This can be effected by building what is essentially a low-frequency transmitter into the wall of a closed stiff tank. If the transmitter is of the electromagnetic type, whose stiffness is low compared to the stiffness of the tank in the frequency range of interest, then the force exerted by the piston can be calculated from the current into the projector, either by measuring or by calculating the force per unit current developed by the piston when it is blocked. When this force is known, the pressure which it produces in an acoustically stiff chamber can be calculated.

This method is applicable only for frequencies far below those for the first chamber resonance of the tank, since, as the tank approaches its lowest resonance, its stiffness drops in value, becoming quite low at the first resonance. Also, at this point, pressure can no longer be considered uniform throughout the tank, and consequently one cannot calculate in any simple manner the pressure at any desired point from the force exerted by the piston. If the walls of the chamber have resonances below the cavity resonance of the chamber, these resonant frequencies reduce even further the upper limit of the useful frequency range. This method has been used with considerable success by USRL with a tank of the type described, built by the Bell Telephone Laboratories.[40] The lowest resonance frequency for this system is about 300 c, so that the system is useful up to about 100 c. In using such a system, one must remember to avoid any condition which lowers the stiffness of the chamber, such as the presence of air bubbles or an acoustically "soft" transducer. Over a limited range, corrections may be made for decreased stiffness due to any effect, provided this stiffness can be measured.

Other quasi-static absolute calibration methods have been employed. One makes use of a condenser-type hydrophone[36] in which the capacitance of the condenser is in one arm of an impedance bridge employing a carrier frequency of 5 kc. Changes in pressure on the diaphragm cause a variation in capacitance which unbalances the bridge. The amount of unbalance becomes a measure of the pressure. This particular system is flat from 0 to 75 c, above which the effect of the first resonance of the hydrophone becomes prominent. Hydrostatic pressure equalization is provided to eliminate the variation of calibration with hydrostatic pressure. If, however, the equalization cannot be carried out, then, by lowering the hydrophone a known distance in water, the absolute calibration can be obtained from the bridge unbalance thus produced. Since the hydrophone is known to have a flat response up to 75 c, this direct hydrostatic pressure calibration is applicable over this range.

5.5.5 Absolute Methods Not Involving Transducers

There are several methods of establishing absolutely the magnitude of a sound field without the use of an electroacoustic transducer. Among these may be listed the Rayleigh disk method, the radiation pressure method, and optical methods. These all require relatively delicate measurements which, while difficult to perform in air, are even more difficult in

water. They are, therefore, of negligible practical significance in underwater sound calibrations.

As evidence of this, consider the use of a Rayleigh disk. This is a thin circular disk suspended from a fine torsion filament so that the plane of the disk makes a definite angle θ with the direction of propagation of the sound wave. If the wave length is much greater than the diameter of the disk, there is a torque exerted on the disk of magnitude

$$M = \frac{2}{3}\rho a^3 v^2 \sin 2\theta \tag{52}$$

where ρ is the density of the medium, a the radius of the disk, and v the rms particle velocity. Expressed in terms of the pressure, this becomes

$$M = \frac{2}{3}\frac{a^3}{\rho c^2}p^2 \sin 2\theta, \tag{53}$$

c being the velocity of sound. Thus, for the same pressure in air and water, the ratio of the torque in water to that in air will be

$$\frac{M_w}{M_a} = \frac{\rho_a c_a^2}{\rho_w c_w^2} = 6.7 \times 10^{-5}. \tag{54}$$

Since torques obtained with the Rayleigh disk are very difficult to measure in air for any reasonable sound pressures, one sees that it would be almost impossible to measure them in water, even if the experimental difficulties in setting up the apparatus could be overcome. The Rayleigh disk and similar methods must be discarded, therefore, as impractical for absolute calibration in water.

Radiation pressure is essentially the steady pressure exerted on a surface when sound is reflected from the surface and is, like the torque in the Rayleigh disk, a second order effect. If a plane sound wave strikes normally a completely reflecting surface, the area of which is numerically much greater than the wave length, the radiation pressure on the surface is given by

$$P = \frac{1}{2}(k+1)\frac{p^2}{\rho c^2}, \tag{55}$$

where k is the ratio of specific heats for the medium (practically unity for liquids), p is the rms sound pressure, ρ the density of the medium, and c the velocity of sound. For a sound pressure of 1 dyne per sq cm in water, the radiation pressure would be about 10^{-10} dyne per sq cm. Obviously, for such low-pressure measurements, very delicate apparatus is required, so that the method is usually of little practical value although it can be used in the laboratory with high sound pressures such as may be developed by quartz crystals at high frequencies.

There are various other methods of calibration characterized by the fact that an electroacoustic transducer is not used, but all are more or less subject to the objection that the measurements are exceedingly delicate. Some are based on the variation of the index of refraction of a fluid with pressure or similar effects. They usually have a limited frequency range over which they can be employed. In comparison with the methods of calibration which can be performed with relative ease, none of them has much practical importance at the present time. Further information regarding them may be obtained by consulting various reference works on acoustics and the general acoustical literature.

5.5.6 The Reciprocity Method of Calibration

By far the most accurate, simple, and generally useful method of absolute calibration is the so-called reciprocity method, based on the reciprocity principle as applied to electroacoustic transducers. Once its advantages are enumerated, the reasons for its adoption as a standard method of obtaining absolute calibrations by USRL are clear. These advantages are:

1. The method is apparently applicable over the entire practical range of frequencies.
2. The actual measurements are easily made and are essentially similar to those employed in relative calibrations (comparison method).
3. The method can be used by relatively unskilled personnel.
4. The measurements may be carried out in the field rapidly and easily.
5. Though the accuracy of the method is at present limited by reflection-interference difficulties, these also limit the accuracy of comparison methods.
6. If certain easily attainable conditions are maintained, there are no theoretical corrections to be applied to the results.
7. Several independent calibrations can be performed at the same time, giving an immediate check on the accuracy of the results.

The reciprocity method is based on the fact that for a passive linear electroacoustic transducer which obeys the reciprocity principle (this includes most transducers now in use), a definite and simple relationship holds between its response as a transmitter and as a receiver. Consider an electroacoustic transducer with its acoustic center (which may be arbitrarily selected) located at a point P_0. The transducer is being operated as a transmitter with a current I flowing into it. At some other arbitrary point P the transducer produces a pressure p. Let S be the transmitting sensitivity expressed as the ratio of the pressure at P to the current I (that is, $S = p/I$). Suppose that there is placed at the point P the center of a source of spherical waves, and let p_c be the pressure produced at the point P_0 when the transducer is not present. If the transducer is present, it develops in this sound field an open-circuit voltage E across its terminals. Let the ratio of E to p_c be the receiving sensitivity M ($M = E/p_c$). The reciprocity principle then states that

$$\frac{M}{S} = \frac{2d\lambda}{\rho c} \tag{56}$$

where d is the distance from P to P_0, λ is the wave length, and ρ and c are respectively the density and sound velocity of the medium in which the transducer is present.

To make use of the reciprocity principle for the absolute calibration of a transducer, three transducers are employed. One is used only as a transmitter or projector, a second only as a receiver, while the third must be a reversible transducer obeying the reciprocity principle. The projector is placed at a point P with a definite orientation. The receiver is placed at a point P' sufficiently distant from P so that the waves reaching it from the projector are essentially plane. Then for a given current I_P in the projector, the voltage developed by the receiver is measured, either on open-circuit or across an impedance kept constant during the measurements. This voltage is denoted by E_{RP}. The receiver is now replaced by the transducer and the open-circuit voltage developed by it, E_{TP}, is measured for the same current I_P in the projector. Next, the projector is replaced by the receiver, whose orientation with respect to the transducer must be the same as it was previously with respect to the projector. The transducer is then operated as a transmitter with a current I_T, and the voltage developed by the receiver E_{RT} is obtained.

If M_R denotes the sensitivity of the receiver and M_T the open-circuit receiving sensitivity of the transducer, then, since the pressure developed by the projector is the same in the first two trials,

$$\frac{M_R}{M_T} = \frac{E_{RP}}{E_{TP}}. \tag{57}$$

If S_T is the transmitting sensitivity of the transducer, that is, the ratio of the pressure produced at the receiver to the current I_T in the transducer, then

$$E_{RT} = M_R S_T I_T \tag{58}$$

since $S_T I_T$ is the pressure at the receiver. From the reciprocity principle

$$\frac{M_T}{S_T} = \frac{2d\lambda}{\rho c} \tag{59}$$

where d is the distance from P to P'. Substituting the value of S_T from equation (59) in (58),

$$E_{RT} = M_R M_T I_T \frac{(\rho c)}{2d\lambda}. \tag{60}$$

Eliminating M_T between equations (60) and (57),

$$E_{RT} = M_R \frac{(M_R E_{TP})}{E_{RP}} I_T \frac{(\rho c)}{2d\lambda} \tag{61}$$

or

$$M_R = \left[\frac{E_{RP}}{E_{TP}} \cdot \frac{E_{RT}}{I_T} \cdot \frac{2d\lambda}{\rho c}\right]^{1/2}. \tag{62}$$

In this way, the calibration of the hydrophone H is expressed in terms of measured quantities. The preceding discussion assumes cgs units for all quantities thus including absolute electrical units. If volts and amperes are used in equation (62), E_{RT} must be multiplied by 10^7. Thus, the absolute calibration may be obtained by a process which involves only electrical measurements on the transducers.

5.5.7 Notes on the Reciprocity Method

To obviate any misunderstanding concerning the use of the reciprocity method of calibration, the following notes are added:

1. The open-circuit voltage developed by the transducer T operating as a receiver should be measured

at the same terminals at which the current into the transducer is measured when operating as a transmitter. The choice of the terminals can be arbitrary to a considerable extent. They may be directly at the electric output of the transducer element itself (for example, the crystal, in a transducer of that type) or at the end of a considerable length of cable. In fact, two terminals of a four-terminal passive electric network may be connected to the transducer, and the terminals used in the calibration selected as the remaining pair of terminals of the network. Any of these conditions is satisfactory, provided the same pair of terminals is used for both current and open-circuit voltage measurement.

2. It is specified above that the distance d should be large enough so that waves from either the projector P or transducer T (when transmitting) are effectively plane at this distance. This is necessary if the plane wave calibration of the hydrophone H is desired. The distance may be shortened if one wishes to obtain a calibration for H in terms of spherical waves of a given radius, or if one can apply a spherical wave correction to reduce a spherical wave calibration to a plane wave calibration. The latter procedure may be necessary if reflection interference is present to a degree which seriously interferes with the accuracy of the measurements. The presence of reflections introduces the same inaccuracies in a reciprocity calibration as in comparison tests, and the methods described in Section 5.3 for eliminating reflection interference may often be profitably applied in reciprocity calibration tests.

3. We have indicated that the choice of the acoustic center of the transducers was arbitrary in the preceding discussion, yet the distance d between centers enters explicitly into the formula for the calibration. This can be understood if one remembers that the receiving response also depends upon the choice of the center, and this latter dependence on d cancels the explicit dependence on d in the formula. See Chapter 4, equation (10). Usually the acoustic center is chosen close to the geometric center of the instrument, but in principle one may take it to be anywhere. If it should be chosen far from the actual instrument, the center must be considered as part of the instrument in requiring that the wave be essentially plane; that is, the plane wave response with such a choice for the acoustic center can be obtained only if the wave from the transmitters is essentially plane, not only over the transducer but over the entire region between the center and the transducer. Thus, there is an advantage, insofar as choice of testing distance is concerned, in selecting the center within, or in the immediate neighborhood of, the transducer.

4. It should be clear that the reciprocity calibration of a transducer can be carried through for any orientation (direction of sound incidence) of the transducers involved, but the same relative orientations must be maintained during the series of tests. One also sees immediately that the directivity pattern of a transducer obeying reciprocity is the same on transmitting and on receiving at the same frequency.

5. One should note that the responses given by the formula represent ratios of magnitudes of quantities without consideration of phase. To obtain the phase of the response, one must include a phase factor, which is not ordinarily known but can be determined in the reciprocity relation shown in equation (56) for the particular reversible transducer. The phase of the response is not usually of interest, but in some cases it may be important.

6. In making a reciprocity calibration one must have a transducer obeying the reciprocity principle, and therefore should have a means of establishing this property. While it is known that it is possible to have a linear passive reversible transducer which does not obey reciprocity, almost all transducers of interest do have this property. No generally applicable conditions have been established to guarantee reciprocity in a transducer, but there are some general principles which serve as useful guides. Theory seems to indicate that if the electromechanical coupling is of the electromagnetic or magnetostrictive type, or a combination of these, reciprocity is obeyed. Similarly, there are indications that electrostatic or piezoelectric coupling or a combination of these also insures reciprocity. A parallel combination of one of the first group (electromagnetic or magnetostrictive) with one of the second (electrostatic of piezoelectric) in general leads to a transducer which does not obey reciprocity. Since such combinations are rare, most actual transducers will apparently obey reciprocity. The condition for reciprocity is sufficiently established if the efficiency of the transducer is 100 per cent. Since no actual transducers attain this efficiency, this criterion is of questionable value for practical application.

One must therefore resort to the criterion of internal consistency between the calibrations obtained with several reversible transducers as a check that they obey the reciprocity principle. It is very unlikely

that, if these reversible transducers did not obey the reciprocity principle, one would obtain the same calibration by the use of each.

7. If a calibrated resistor is available so that current can be measured by measuring the voltage drop across the resistor in series with the transducer, one need not have an absolutely calibrated voltmeter to perform a reciprocity calibration. For, if one substitutes E_I/R for I_T in equation (62), it can be seen that only the ratio of voltages, and not their absolute magnitudes, enters into the formula.

5.5.8 Motional Impedance Methods

There have been proposed and applied several methods of absolute calibration, based on the measurement of the impedance of the transducer, which can be applied to transducers obeying the reciprocity principle. It is sufficient here to indicate how one of these methods leads to an absolute calibration. If one considers a transducer which has a sharp mechanical resonance at some frequency, the impedance shows a rapid variation with frequency in the neighborhood of the resonant value. If one plots the resistance and reactance as a function of frequency, smooth curves can be drawn connecting the portions of the resistance curve and the reactance curve far above and far below resonance. These curves are referred to as the *blocked resistance* and *reactance,* since they correspond to the impedance which would be measured if the diaphragm of the transducer were prevented from moving.

The difference between the actual impedance and the blocked impedance is referred to as the *motional impedance.* If the motional resistance is plotted against the motional reactance in rectangular coordinates, with frequency as parameter, a figure is obtained known as the *motional impedance circle.* If one measures the diameter of the motional impedance circle in ohms for the instrument immersed in water and then in air, calling the quantities D_W, and D_A respectively, one can show that the efficiency E of the transducer in water, that is, the ratio of acoustic power output to electric power input, at resonance, is given by

$$E = \frac{D_W}{R}\left[1 - \frac{D_W}{D_A}\right] \tag{63}$$

where R is the actual resistance of the device in water.

The directivity pattern and thus the directivity index of the transducer can be measured with an uncalibrated transducer. From equation (8), Chapter 4, one can see that, if the efficiency and directivity index of a transducer are known, its response can be determined. In this way, the device can be absolutely calibrated at its resonant frequency from the motional impedance circle (which gives the efficiency) and a directivity pattern (which gives the directivity index).

Since this method furnishes an absolute calibration at only one frequency, it is not of great value as a general calibration method, but it is useful for obtaining the efficiency of a device at resonance by purely electrical impedance methods. Some of the other methods of motional impedance analysis are more refined and allow calibration over an extended frequency range, but in general they are not so convenient to use as the reciprocity method.

5.5.9 Relative Calibration of Transducer

Even the reciprocity method entails more effort than is desirable for the calibration of most devices. The comparison method, involving the calibration of one transducer against another which has already been calibrated, provides a practical means for the rapid calibration of most devices. In the comparison method the magnitude of the sound field is first established by means of a previously calibrated standard. This is then followed by the calibration of the device to be tested in this known sound field.

It is presumed in a calibration by comparison that the reference standard is sufficiently stable in construction and operation so that its calibration is retained in the interim between its own calibration and its application in a relative calibration. Either a transmitter or a receiver can be used as a reference standard, the former to establish a known sound field, the latter to measure the magnitude of the sound field produced by an uncalibrated transmitter. It has been found by USRL that properly constructed receivers are somewhat more reliable than transmitters as reference standards, but the difference is not great. In fact, by using both a calibrated receiver and a calibrated transmitter in a comparison test, a cross check on the stability of the standards may be obtained in conjunction with the test.

The procedure in the relative calibration of a receiver is the following: A transmitter is placed at one point in the water and driven by a constant voltage

(or current) at some frequency. A standard receiver is then placed at an appropriate position in the sound field, and from its generated voltage the magnitude of the sound field can be obtained. The reference standard is then replaced by the receiver under test and its generated voltage obtained, giving its response at that frequency. The frequency may be swept during each test, and then, by comparing measured values of the generated voltage of the standard and the transducer under test at equal frequencies, the frequency response characteristic of the transducer may be obtained.

It should be noted that, if a plane wave calibration of the instrument is desired, then, at the position selected for the receivers, the waves from the transmitter must be essentially plane with respect to the instruments. Whether or not this is the case depends, among other things, on the nature of the instruments themselves, particularly on their size. Because of these conditions, the waves at one point may be essentially plane for one receiver but not for the other. In this case, it may be more convenient to test the two instruments at different distances from the source. This may be done, provided both distances lie in the inverse-square-law region for the source, so that only an inverse-square-law correction need be applied. In some cases one may find it desirable or expedient, because of the presence of reflection interference, to operate the instruments at closer distances and to apply a spherical wave correction to the result, as has been described previously.

In calibrating a transmitter, one uses a calibrated standard receiver which is located in the inverse-square-law region of the field of the transmitter. The pressure produced at this point can then be determined from the voltage generated by the receiver. Again, it may be desirable or expedient to locate the receiver closer to the transmitter and apply a spherical wave correction.

Since a relative calibration is based on the stability of calibration of the standard, frequent checks on the calibration of the standards must form a regular part of any testing program extending over a long period of time. These checks are most conveniently made at regular intervals by means of the reciprocity method. The reciprocity method is particularly valuable for this purpose at a test station since the procedures used are the same as for relative calibrations. Thus the equipment necessary for a reciprocity calibration is available at all times and no extra equipment is necessary. A running check on all tests may be made by using several standards and checking the calibrations thus obtained against each other. A calibrated transmitter may serve as one of the standards.

5.5.10 The Choice of Standards

For maximum accuracy, reliability, and general versatility, a standard should possess certain characteristics which are outlined below.

Stability With Time

Stability is essential, since the accuracy of a relative calibration is limited by any change in the response of the standard from the time that it was calibrated to the time of its use. For this reason, it should be sufficiently rugged so that slight jars do not change its calibration, and it should be constructed of materials whose properties do not change with time. If it contains permanent magnets, their flux density should be permanent. The stiffness of springs should not vary as a result of aging, or of cold working resulting from their extension and retraction. The instrument should be constructed so that dampness or moderate heat or cold do not change its calibration, and all exposed parts should be resistant to corrosion.

Temperature Independence

It is desirable that the response of a standard be independent of temperature over the useful frequency range of the instrument, since the temperature rarely can be controlled in calibration tests. Otherwise, it is necessary to know how the calibration varies with temperature, which would require considerable additional labor. Temperature dependence of response is an important factor in working with Rochelle salt crystal devices because of the rapid variation of the dielectric constant of x-cut crystals and consequent change of impedance in the neighborhood of the upper Curie point (24 C or 75 F). This temperature variation does not have a serious effect upon the response of a Rochelle salt crystal receiver if the impedance into which the crystal operates is high compared to its own impedance. For a Rochelle salt crystal transmitter, the response expressed in terms of pressure per unit current input does not vary appreciably with temperature, although the response expressed on a per volt or per available watt basis may vary greatly. It is therefore desirable to operate Rochelle salt crystal projectors on a constant current

basis, which may be accomplished by making the source of electrical power have a high output impedance compared to the impedance of the crystal.

Wide-Band Uniform Response

It is desirable that a standard have a smooth frequency response over a wide frequency band. Rapid variations in response with frequency make it difficult to compare the responses of two instruments in such a range because of the difficulty of reading accurately a steep curve on a recorder chart. A wide frequency band is desirable so that the number of standards required to cover the entire frequency range of interest be as small as possible to reduce rigging time. For high-frequency transmitters it is difficult to obtain a flat frequency response. However, a smoothly varying response is in general satisfactory and can be obtained readily with crystal projectors.

Linearity, Large Dynamic Range

Over the range of pressures which a standard is required to measure or to produce, the device should be linear; that is, the voltage produced by a receiver at each frequency should be proportional to the pressure of the sound field in which it is contained, and the pressure produced by a transmitter at some point in the field at each frequency should be proportional to the input current or voltage applied to it. When nonlinearity occurs, a sinusoidal input signal (electric or acoustic) no longer, in general, produces a sinusoidal output of the same frequency. Most instruments, however, are linear over a limited range of input signal amplitudes. For the greatest usefulness of a standard, this dynamic range should be as great as possible, as this allows a large range of sound field pressures to be produced or measured by a single instrument. Since a transmitter may have variations in response with frequency of 50 db or more, in order to make a comparison calibration with a single standard receiver, the standard must have a corresponding dynamic range as limited by nonlinearity on the high end and inherent noise on the low end.

Low Threshold

The lowest pressure that can be measured by a receiver is determined by its inherent noise voltage. This may be due to thermal noise, vacuum-tube noise (of an associated preamplifier), contact noise, or other similar factors. At each frequency, the pressure at which the signal voltage of the instrument is equal to the noise voltage, in a 1-c band centered at the frequency, is known as the threshold of the transducer. It is desirable to have the threshold of a standard as low as possible in order to extend the dynamic range as far as possible in the direction of low pressure.

Reasonably High Response

The magnitude of the response of a standard can be of considerable importance independent of its inherent noise characteristic. For example, if the response is low, the electric crosstalk between a receiver and a transmitter may exceed the level of the electrical signal to be measured. A similar situation applies with respect to the use of a transmitter as a sound source. Because of the presence of ambient noise in the water, it is necessary that the response of a transmitter standard be sufficiently great so that its sound field exceeds the ambient noise sound field.

A variety of standard transducers have been developed which satisfy the conditions outlined above. Their characteristics are given in another part of this volume.

5.6 CALIBRATION OF DEVICES COVERING WIDE FREQUENCY RANGES

When a transducer is being used for wide-band reception, a single frequency calibration is still significant, because, if the device is linear, its wide-band response can be determined from the single frequency response by superposition in accordance with Fourier's theory. The calibration then consists in determining over what range the hydrophone is linear and in taking a single frequency characteristic within that range. The procedure for taking a single frequency characteristic has been described. The linearity at any given frequency is best observed by varying the input level at that frequency and seeing whether or not the output level follows proportionately. Instead of taking a single frequency characteristic, it is, of course, also possible to measure the response for a signal with any type of frequency spectrum.

In particular, the response may be measured for a signal consisting of very complex aperiodic wave forms. Such signals usually are referred to as noises. The sound created by thermal agitation, the so-called thermal noise, is an illustration in point.

The measurement of such signals places quite severe requirements on the measuring system. It is

usual to measure the overall signal level and to obtain a frequency analysis of the noise. Often the time variation of the noise is of interest. This can be obtained in the form of a time-level distribution or as the *crest factor* of the noise. This latter is defined as a ratio of the crest value to the effective value of the quantity.

The overall signal level is determined with a wide-band measuring circuit. This circuit must carry the highest noise peak without overloading and include a square-law measuring device, which is the only type that adds up the contributions of the various frequencies in the signal in such a way as to give the rms signal level.

A frequency analysis can be obtained by sweeping over the frequency range of the noise with a narrow heterodyne band-pass filter. The design of this filter must be carefully considered from the standpoint of transient response. The requirements for the rest of the system are the same as those discussed above for measuring the overall signal.

The crest factor can be measured by obtaining a wide-band response with a square-law rectifier (thermocouple) and by obtaining the peak response on an oscilloscope.

One of the difficulties in all of these measurements is the requirement of using a square-law measuring device. The only true square-law device is the thermocouple, but this is so slow-acting that it can furnish only a long time average and has a limited dynamic range. Therefore, vacuum-tube detectors are usually used. These are fast, but they follow the square law only over a limited range of input levels. The question then arises as to whether or not the noise can be satisfactorily measured with the particular rectifier available. One method that has been used to answer this question consists of measuring the crest factor and determining whether or not the rectifier is still square law for the highest peaks in the noise. While this method is helpful, there is theoretically some question as to whether it is a sufficient criterion. It is therefore desirable to consider the problem from other angles as well. Sometimes previous measurements on similar noises which have been satisfactory are available. At other times an assurance can be developed from a study of the data itself.

The above requirements on the measuring system, namely, that it (1) shall not overload on the highest noise peaks, (2) shall adequately cover the frequency range of the noise, and (3) shall have a square-law rectifier, are sufficient to obtain a level measurement and a frequency analysis of the noise. In some cases it is desirable also to obtain a graph of the noise or to view it on the oscilloscope. In such cases, it is necessary that the phase relations between different frequencies be maintained as well as the magnitudes. This adds another requirement, namely, that the system have its phase shift linear with frequency.

The requirements of the pick-up device used in the tests are similar to those on the circuits of the system. If the hydrophone has a uniform response over the frequency range of interest, which usually implies a phase shift linear with frequency, it will be satisfactory for use in these tests both for obtaining a level measurement and also from the standpoint of maintaining phase relations.

Chapter 6

DESCRIPTION AND OPERATIONAL PROCEDURES OF THE USRL TEST STATIONS

By *Erhard Hartmann* and *Earle C. Gregg, Jr.*

6.1 DESCRIPTION OF MOUNTAIN LAKES TEST STATION

6.1.1 Site of Station

THE MOUNTAIN LAKES test station is located on Crystal Lake in the township of Mountain Lakes, New Jersey. This lake is about 650 yards long and 230 yards wide, and has a small island approximately at the center.

The depth of the lake is fairly uniform, averaging about 15 feet. The bottom is a thick stratum of mud, which has good sound-absorbing properties, especially at supersonic frequencies. The mud, however, contains some decomposing organic material which produces gas bubbles. Since these are good reflectors of sound, the top layer of the mud which contains the decomposing material has been removed from the bottom of the test areas by dredging. The depth of the water in these areas has been accordingly increased to about 18 feet. In addition, the lake has been treated frequently with copper sulphate to retard decomposition and the growth of algae.

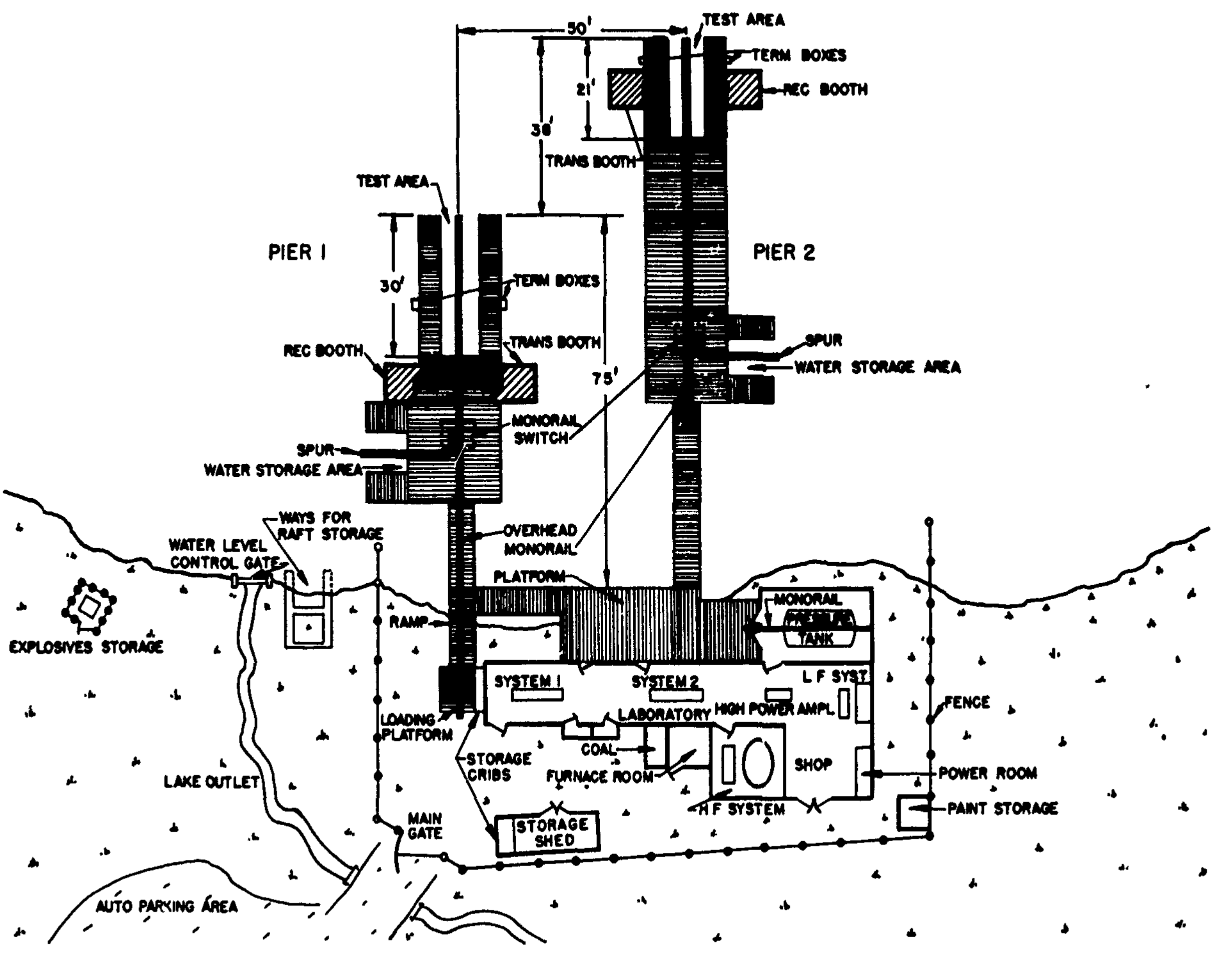

FIGURE 1. Plan view of Mountain Lakes laboratory and grounds.

FIGURE 2. View of Mountain Lakes laboratory from Pier 2.

6.1.2 Facilities

The Mountain Lakes test station provides facilities for the calibration of underwater acoustic devices from a frequency of 2 cycles per second to 3.5 megacycles per second.[a] This range is covered by means of four separate testing systems. A low-frequency tank system covers the frequency range from 2 c to about 100 c. Associated with this system are facilities for varying the temperature and hydrostatic pressure.

[a] Transducers available at present will operate up to 2.2 mc.

Two intermediate-frequency units, designated system 1 and system 2, are used with outdoor piers for free field calibration in the lake. Both systems will operate from 15 c to 150 kc and can be arranged to test apparatus with power inputs up to 1,500 watts. The apparatus has been assembled in bays and arranged to provide maximum separation between high- and low-level signal paths to minimize cross talk. This practice of separation has been maintained throughout both systems, including the transmission lines and transducer coupling booths on the piers. Finally, a high-frequency unit which includes an elliptically shaped tank covers the range from 100 kc to 2.2 mc. This unit may also be used in conjunction with one of the piers.

Other acoustic testing facilities include an open tank with sound-absorbing walls (a type used for production testing by the Western Electric Company) and a closed cylindrical tank about 15 feet long and 8 feet in diameter. The latter can be used at hydrostatic pressures up to 300 lb per sq in. and at frequencies up to about 150 kc. Tests at high pressures

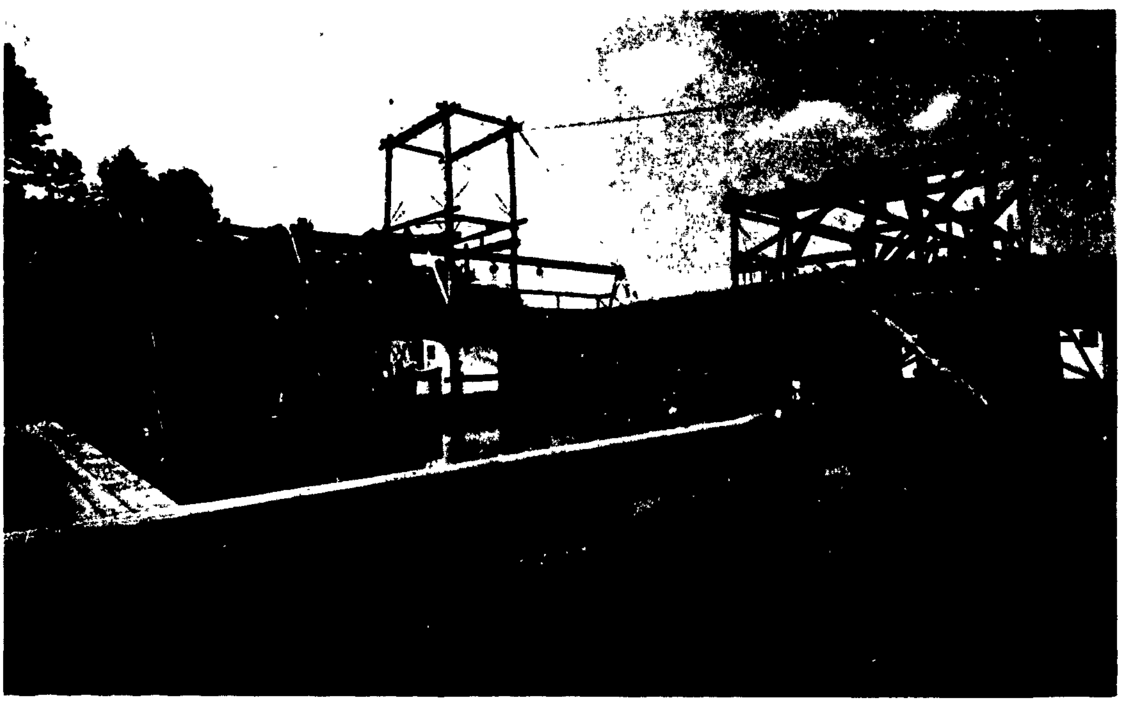

FIGURE 3. Testing piers at the Mountain Lakes station. The booths housing terminal equipment and the overhead monorail systems are visible.

FIGURE 1. General view of test area of Pier 1. Several suspension carriages and the rotator are visible. Apparatus in foreground is being used to make impedance measurements.

are of interest in connection with underwater sound gear used on submarines.

One of the two outdoor piers is equipped for handling devices, weighing as much as 2,000 pounds, by chain hoists travelling on an overhead rail between the loading platform and the far end of the pier. The second pier is equipped for devices of not more than 250 pounds. For testing distances greater than those provided by the piers, a raft with a working load capacity of 3,000 pounds is available. Signal transmission and power cables extending from the laboratory to a position 250 yards out in the lake provide facilities for operating equipment on this raft.

The laboratory has its own machine shop, water supply, and heating system. Compressed air and electric power are available throughout the building. Auxiliary equipment includes meters for measuring current, voltage, or power; impedance bridges; vacuum-tube test sets; cathode-ray oscilloscopes for observing wave shapes; and filters for limiting frequency bands.

The electric energy is supplied at 230 volts, 60 cycles, with the midpoint grounded. This voltage is used on the larger motors. The 115-volt supply is regulated to keep a uniform voltage on the signal generators, amplifiers, detectors, and recorders.

All high-voltage requirements are supplied by regulated rectifiers associated with the various system components. Thus, drifts in the calibrating apparatus resulting from variation in the supply voltage are held at a minimum. A 24-volt d-c supply for the operation of relays and indicator lamps is obtained from rectifiers energized by the 115-volt line.

Most of the electrical equipment was designed and constructed by the Bell Telephone Laboratories under contract with the National Defense Research

Committee [NDRC]. The Underwater Sound Reference Laboratories have designed and constructed most of the mechanical equipment and have developed the high-power equipment, the pulsing system, the polar recording system, and certain additional features needed for special testing.

6.2 CALIBRATION AND TESTING EQUIPMENT AT MOUNTAIN LAKES

The calibration and testing systems of USRL are described on the basis of their present status. It should be emphasized, however, that developments in sonar gear and the constantly improving techniques in testing are making new demands, in many cases beyond the capacities of existing equipment. It must therefore be constantly changed and improved to maintain the standards required of a reference laboratory.

For example, system 1, installed in June 1942, incorporated a narrow band-pass filter which discriminated against noise and other interference. This was at the time a distinct improvement but after the development of the pulse method, which requires a wider transmission band, system 1 was inadequate. For this reason, and also because of the increasing importance of noise analysis, system 1 is now limited in its applications, and a continuously increasing proportion of the work is handled by system 2.

6.2.1 Electrical Components of Systems

The essential parts of systems 1 and 2 are described in a sequence which traces a typical signal from the generator to the projector and from the hydrophone to the recorder.

Test Signal Generators

The primary signal generators are beat-frequency oscillators covering the 15-c to 150-kc range with a response uniform within 0.3 db. A visual indication of the frequency setting is provided by a calibrated scale on a strip of 35-mm motion picture film 30 feet long, coupled through a sprocket chain to the air condenser controlling the frequency. The length of this scale indicates the degree of frequency resolution. The shape of the condenser plates is such that the scale gives adequate frequency resolution throughout the entire range.

A synchronous motor drive provides the lock-in between oscillator and recorder when frequency-re-

Figure 5. View of raft.

sponse traces are taken, although the dial may be operated manually.

The heterodyne oscillator assembly contains three separate circuits. Two of them operate as a beat-frequency oscillator, one fixed at 650 kc and the other variable from 500 to 650 kc. The difference frequency of the heterodyned outputs furnishes the signal range 0 to 150 kc. This arrangement is identical in both systems, but the third circuit is fixed at 678 kc in system 1 and at 747 kc in system 2 for use in tuning the detector circuit described later in this section.

Frequency stability has been obtained by design features such as (1) mounting the three oscillator circuits in the same chassis to have the same ambient temperature, (2) separating the component parts with networks and buffer amplifiers, and (3) using suitable shielding and filters. To correct for the slight drift in frequency that still may occur, means for adjusting the carrier frequencies are provided and the frequency scale can be checked by aligning with the 60-c power supply and with a 100-kc crystal shunted across the oscillator output. Since the adjustment is based on the difference frequency, no attempt is made to observe the actual frequencies of the carrier oscillators.

The oscillator furnishes a maximum output level of 150 db vs 10^{-16} watt adjustable over a 40-db range. Harmonics in the output voltage are at least 40 db below the fundamental, and a minimum signal-to-noise ratio of 50 db is realized.

In system 2 a thermal noise signal may be generated by using the noise generator in conjunction with the heterodyne oscillator. The noise generator includes a voltage regulator tube functioning as a wide-band

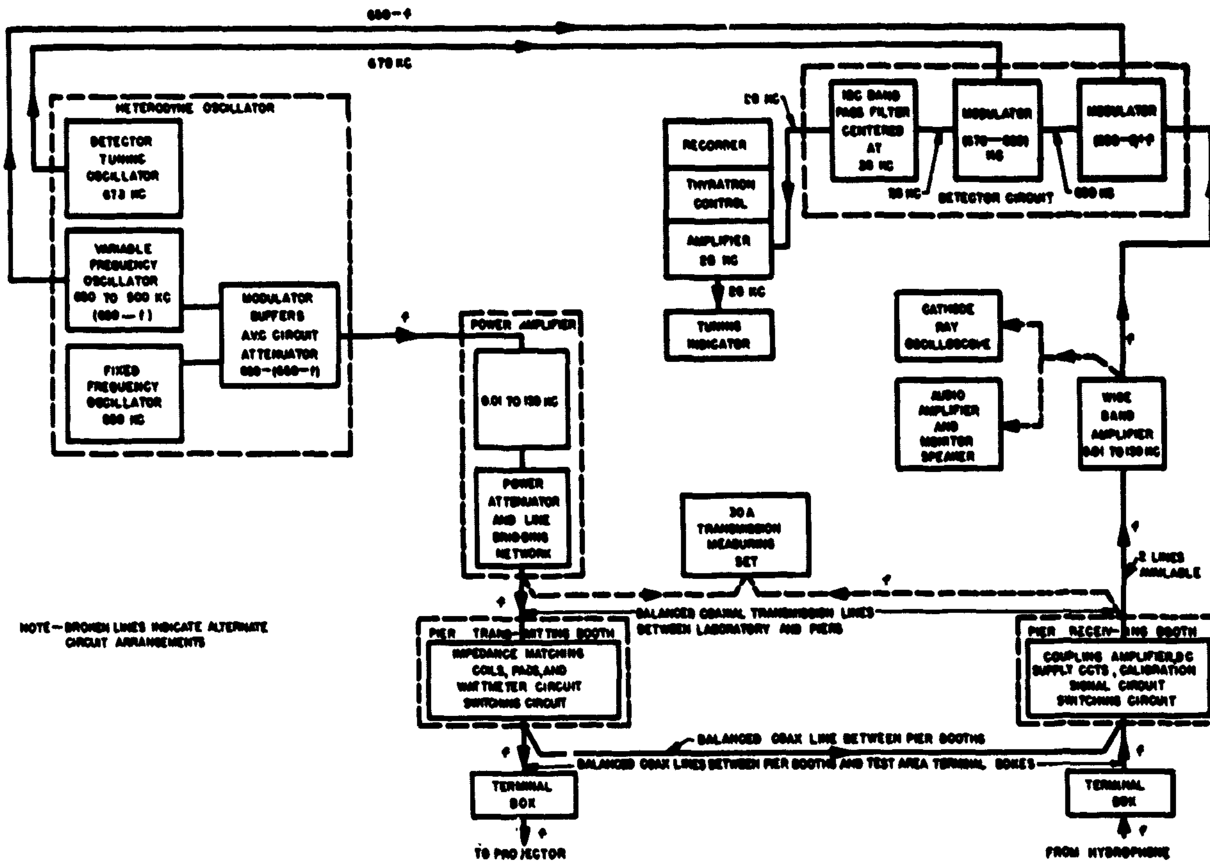

FIGURE 6. Block diagram of 15 c to 150 kc System 1.

thermal noise source. Two band-pass filters limit the frequency spectrum to 650 ± 0.15 kc or 650 ± 3 kc, as desired. These signals are used to replace the fixed 650-kc signal in the heterodyne oscillator. The final signal output is then a band of thermal noise 300 c or 6,000 c wide, centered at the frequency given by the oscillator setting.

The noise output should be at least 10 db below the single frequency output to prevent *peak clipping* in the modulator circuit. This adjustment is made by controlling the output of the noise generator circuit.

The midpoint of the noise band in this generator is 650 kc for correct frequency alignment of the output band. The frequency range of the variable oscillator must be exactly 650 kc to 500 kc. To obtain this condition, adjustments are made on the generators as follows: The noise generator circuit, functioning only as an amplifier, is sharply tuned by a filter 20 c wide centered at 650 kc. This is connected between the fixed-frequency oscillator and the following modulator. The fixed oscillator is then tuned for maximum output at any convenient frequency setting. With the frequency of the fixed oscillator thus established at 650 kc, the frequency scale is aligned at 60 c and 100 kc by adjustments on the variable oscillator.

Power Amplifiers

Power amplifiers with a maximum gain of 40 db are associated with each system. The maximum undistorted power level of system 1 is 177 db and that of system 2, 173 db, but an auxiliary amplifier, described later, may be used with either system to reach an undistorted level of 192 db vs 10^{-16} watt, or about 1,500 watts.

System 1, covering the range from 15 c to 150 kc, requires two output transformers for its power amplifier. Automatic transfer between them is effected near 2 kc by a switching circuit operated by a cam on the oscillator frequency dial. System 2 employs two power amplifiers, covering ranges from 15 c to 30 kc and from 300 c to 150 kc. The amplifiers of both systems have been designed to operate into a load impedance

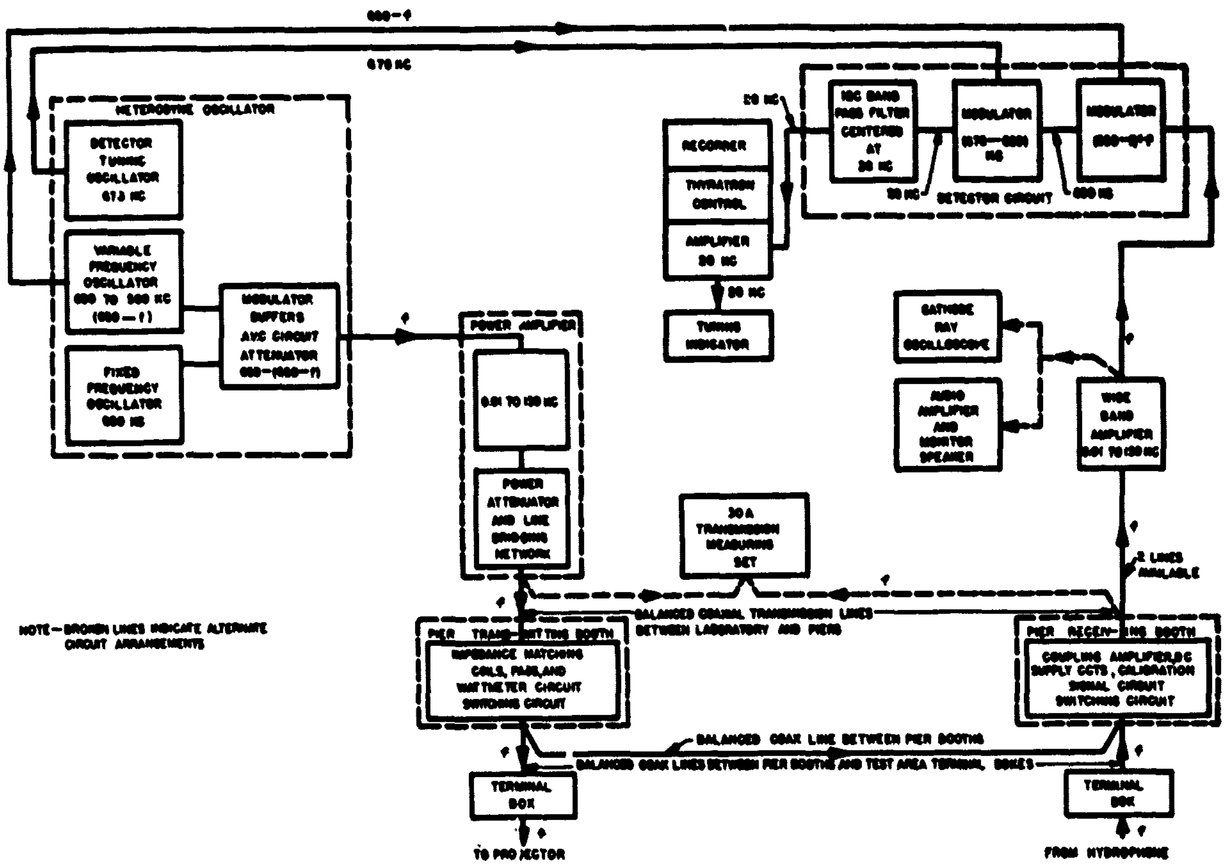

FIGURE 6. Block diagram of 15 c to 150 kc System 1.

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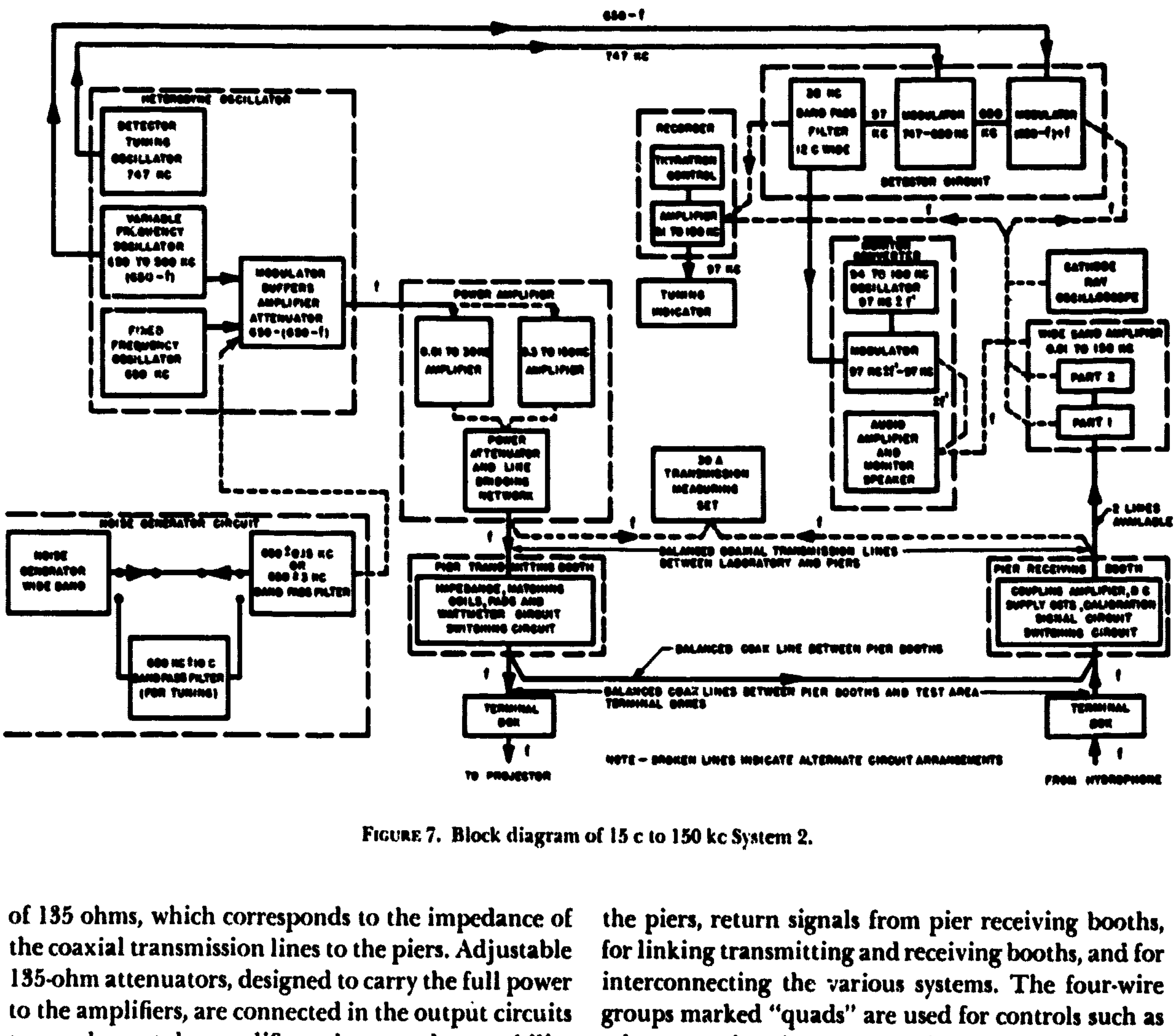


FIGURE 7. Block diagram of 15 c to 150 kc System 2.

of 135 ohms, which corresponds to the impedance of the coaxial transmission lines to the piers. Adjustable 135-ohm attenuators, designed to carry the full power to the amplifiers, are connected in the output circuits to supplement the amplifier gain controls, to stabilize the output impedance, and to improve the amplifier signal-to-noise ratios. The amplifier design and the use of output attenuator pads permit a 55-db margin between signal and amplifier noise. A bridging network of 30-db loss at the amplifier output terminals allows a 30A transmission measuring set, described later in this section, to be used for monitoring purposes.

Transmission Lines

The 135-ohm insertion loss of the combined transmitting, receiving, and pier booth cross-connecting lines does not exceed 0.25 db at 150 kc, which is too small to require any correction for line attenuation.

Balanced coaxial lines (Figure 11A) are used for signals from power amplifiers to coupling booths on the piers, return signals from pier receiving booths, for linking transmitting and receiving booths, and for interconnecting the various systems. The four-wire groups marked "quads" are used for controls such as relay operation, intercommunication, and indexing.

The requirements to prevent cross talk are severe, as is indicated by the difference in outgoing and incoming levels that may exist. For instance, the hydrophone level in the receiving line may be as low as 10^{-16} watt, while the power supplied to a projector over the transmitting line may be 150 db above this level. In order not to affect the measurements, the cross talk must be lower than the received level by at least 15 or 20 db, which requires a margin between the transmitting and receiving apparatus of nearly 170 db. In addition to the use of coaxial cable, other precautions tending to minimize cross talk have been observed, such as a minimum spacing of 6 feet between all transmitting and receiving lines, and careful attention to the laboratory grounding system as described later in this section.

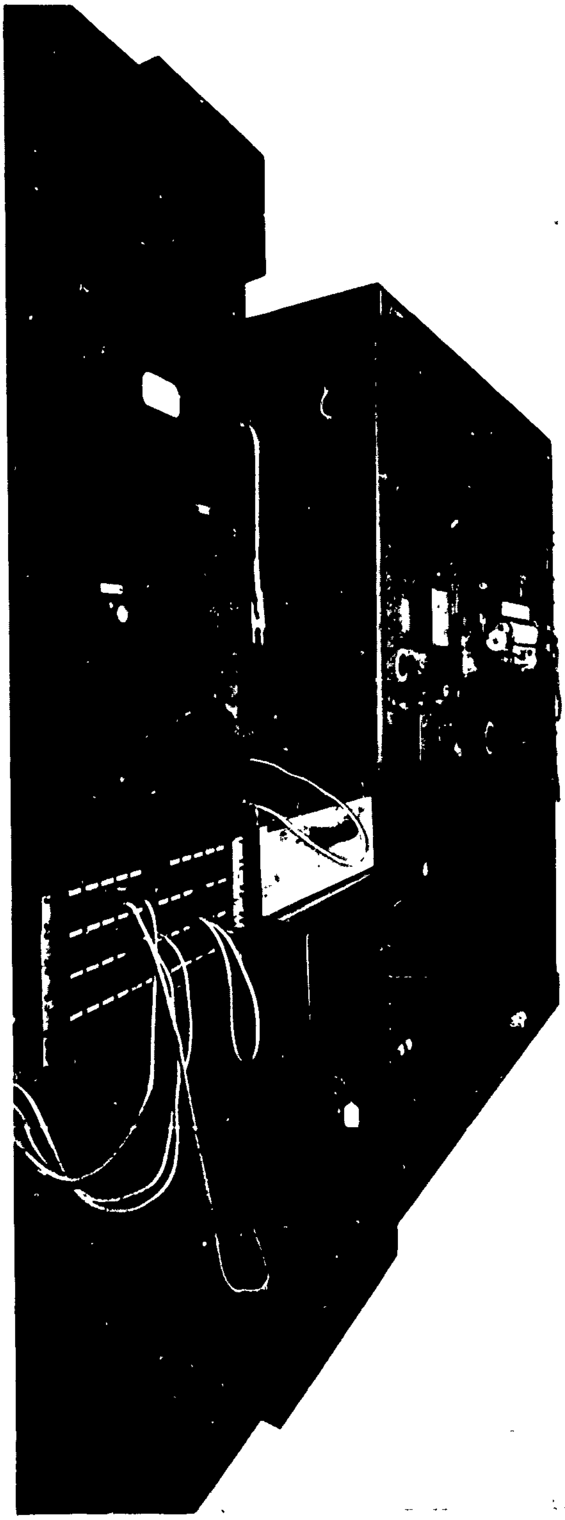


FIGURE 8. 15 c to 150 kc recording system. Bay on left shows receiving amplifier and detector. To the right, shown in order, are signal and noise generators, recorder and thyratron control panel, and power amplifiers.

While the lead-covered coaxial lines provide excellent transmission, equally good performance for comparatively short runs can be obtained from a twisted pair of flexible, single coaxial cables (Figures 11B and 11C). The rubber-covered cable is used for lines that are exposed to the weather; the cotton-braid covered one for inside connections.

Projector Coupling Equipment

The projector coupling apparatus is housed near the test area in the transmitting booth. The primary function of this equipment is to provide suitable impedances for matching the various test projectors as they are connected to the 135-ohm transmitting line. Repeating coils provide various sending impedances. H-type resistance pads, designed to be used between each sending impedance and 135 ohms, permit the measurement of available power at any sending impedance. Two repeating coils are available for handling power outputs up to 100 watts. One of these has seven secondary windings terminating in a multi-contact receptacle. The sending impedance is varied by inserting in this receptacle one of seven plugs, with contacts strapped together in various patterns so that impedances of 4, 9, 16, 25, 36, 49, or 64 ohms may be provided. The second coil provides impedances of 135, 600, or 2,400 ohms. A third coil handles power outputs up to 1,000 watts at 50, 100, or 500 ohms, and resistance pads are available for measuring the available power at these high outputs. A wattmeter circuit for measuring actual power delivered to the projector is also available.

Hydrophone Coupling Equipment

The hydrophone coupling apparatus is housed on the piers in the receiving booths. Its primary function is to provide suitable coupling between hydrophones and the 135-ohm receiving lines to the laboratory.

A battery-operated preamplifier of novel design provides for either balanced or unbalanced operation. A switch in one position sets the input circuit for balanced operation. In this case impedance may be represented by a shunt resistance of 100 megohms and a shunt capacitance of about 5$\mu\mu$f, with a ground at the electric center. In the other position the input impedance is set for unbalanced operation and may be represented as a shunt resistance of 50 megohms and a shunt capacitance of about 10$\mu\mu$f, with one terminal at ground. The amplifier output has been designed to feed into the 135-ohm receiving line. The

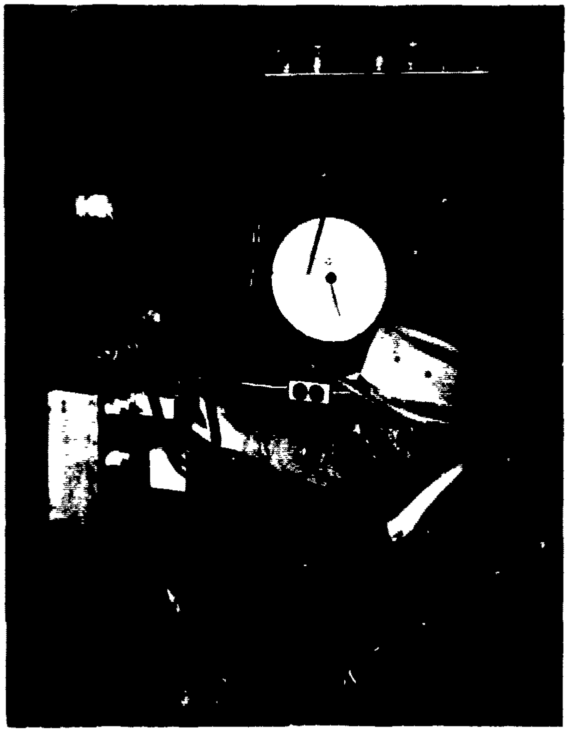


FIGURE 9. Interior of transmitting booth.

FIGURE 10. Interior of receiving booth.

frequency characteristic is essentially flat through the range from 15 c to 150 kc and the voltage gains for the unbalanced and balanced input conditions are approximately +0.5 db and −6.0 db, respectively.

A battery supply and coupling circuit is provided for the frequently used standard hydrophones such as the 3A, 5C, and 5D types. A metering panel permits monitoring of all A and B voltages and currents. Switches and jack-terminals provide for measurements of various quantities, such as response, coupling, and available power. To calibrate a hydrophone on open circuit requires a knowledge of the loss in the coupling circuit. The procedure for determining this is to place in series with the hydrophone a resistance which is very small in comparison with the resistance of the instrument. A variable oscillator of low voltage is applied to this resistor and the signal is carried through to the recorder as though from the hydrophone itself. After the range of frequencies has been covered, the same voltage is connected directly to the recorder and the range swept over again. The difference between the records in db is the loss in the coupling circuit.

Various types of supplementary apparatus are frequently required. One such device is a portable battery-operated preamplifier that may be placed at the edge of the testing area in order to reduce the length of the hydrophone cable. Another is an underwater preamplifier, operated from the battery for use with high-impedance instruments, such as tourmaline gauges (tourmaline crystal hydrophones). This amplifier, mounted in a watertight housing, is equipped with cable glands for hydrophone leads, battery supply connections, and lines for calibration and output signals. Several special battery supply, coupling, and metering circuits for miscellaneous standard hydrophones are available. Portable low-power d-c supply circuits, suitable for various preamplifiers, have been designed and are discussed later.

RECEIVING AMPLIFIERS

In both system 1 and system 2, high-gain, wide-band, low-noise-level amplifiers are used to increase the incoming signal to levels suitable for recording. The frequency characteristics of these amplifiers are flat within 0.2 db from 15 c to 150 kc.

The coaxial lines are coupled to these amplifiers by magnetically and electrically shielded input transformers, with the input winding balanced to ground. These receiving amplifiers use four low-noise-level

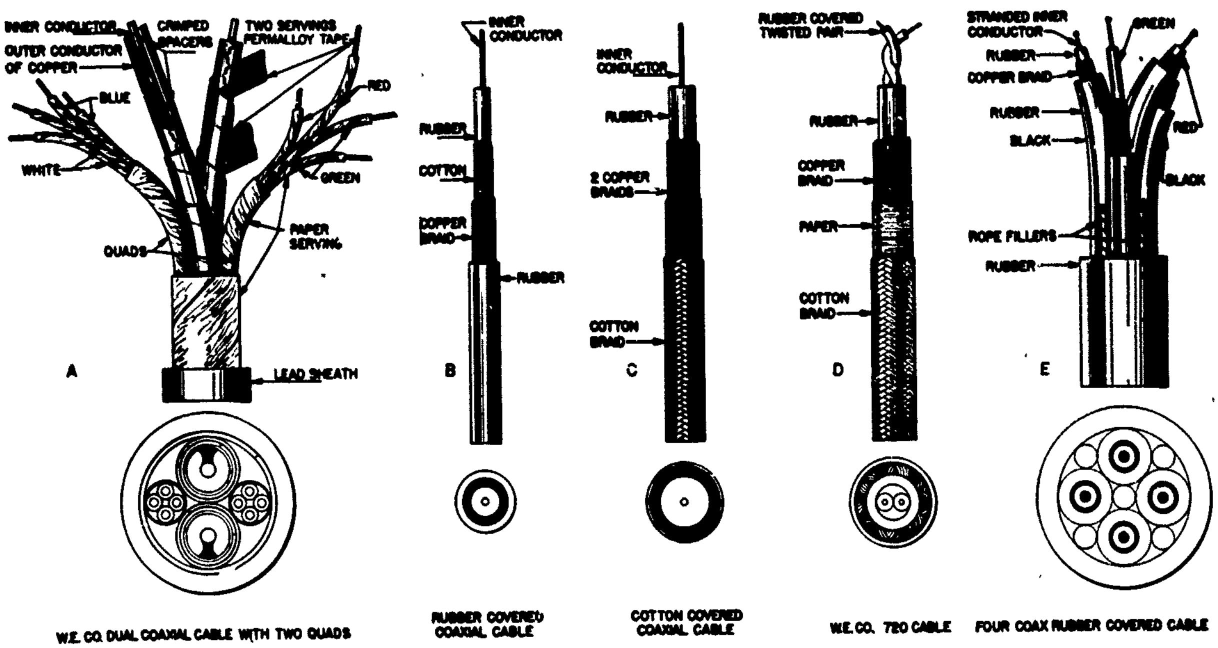


FIGURE 11. Types of coaxial cable used by USRL.

tubes, heated by regulated direct current, which have a maximum gain of approximately +60 db (variable in 10-db steps) between the 135-ohm transformer input and a 600-ohm cathode-follower output circuit. The gain is controllable from −20 db to +60 db by a split attenuator, comprising two 40-db sections, connected at the grids of the first and third stages. The attenuation preceding the first stage is completely inserted before attenuation of the second section is introduced, though both are operated from a single shaft. Improved signal-to-amplifier noise margin and higher undistorted output levels are obtained by this method of gain control.

In the receiving amplifier of system 2 is a second attenuator covering 10 db in 1-db steps. There is also included a supplementary amplifier, continuously adjustable from approximately +20 db to +25 db, that is used with the primary receiving amplifier when additional gain is required.

DETECTORS

Detector circuits are used with each system for obtaining frequency discrimination against background and inherent noise, harmonics, and waterborne interference, particularly that from the other system.

The general principle of operation is shown in the system block diagrams (Figures 6 and 7). The input signal f is impressed on the grid of a balanced carrier suppression-type modulator through an attenuator and a 150-kc low-pass filter circuit. The carrier frequency, 650 kc $- f$ kc, is brought to this modulator from the signal generator through a tuned buffer amplifier, controlled by an automatic volume control circuit. The buffer amplifier is used primarily to obtain an adequate margin between the carrier level and the maximum signal level in order to minimize the unwanted modulation products other than the sum frequency. The output of the first modulator is then passed through a buffer stage incorporating tuned circuits. The tuned circuits pass only the sum frequency, $(650 - f) + f = 650$ kc, which is impressed on the grid of the second modulator. The second carrier frequency, from the detector tuning oscillator circuit of the signal generator, is brought to this modulator through a tuned buffer amplifier, which has primarily the function of providing an adequate carrier-to-signal level margin. In system 1 the detector tuning frequency is 678 kc. The 28-kc difference frequency from the second modulator is then impressed on a crystal filter having an essentially square-top pass band of about 12 c centered at 28 kc. The filter is followed by one stage of tuned amplification terminating in 135 ohms.

The detector circuit of system 2 has three acceptance band widths provided by three crystal filters.

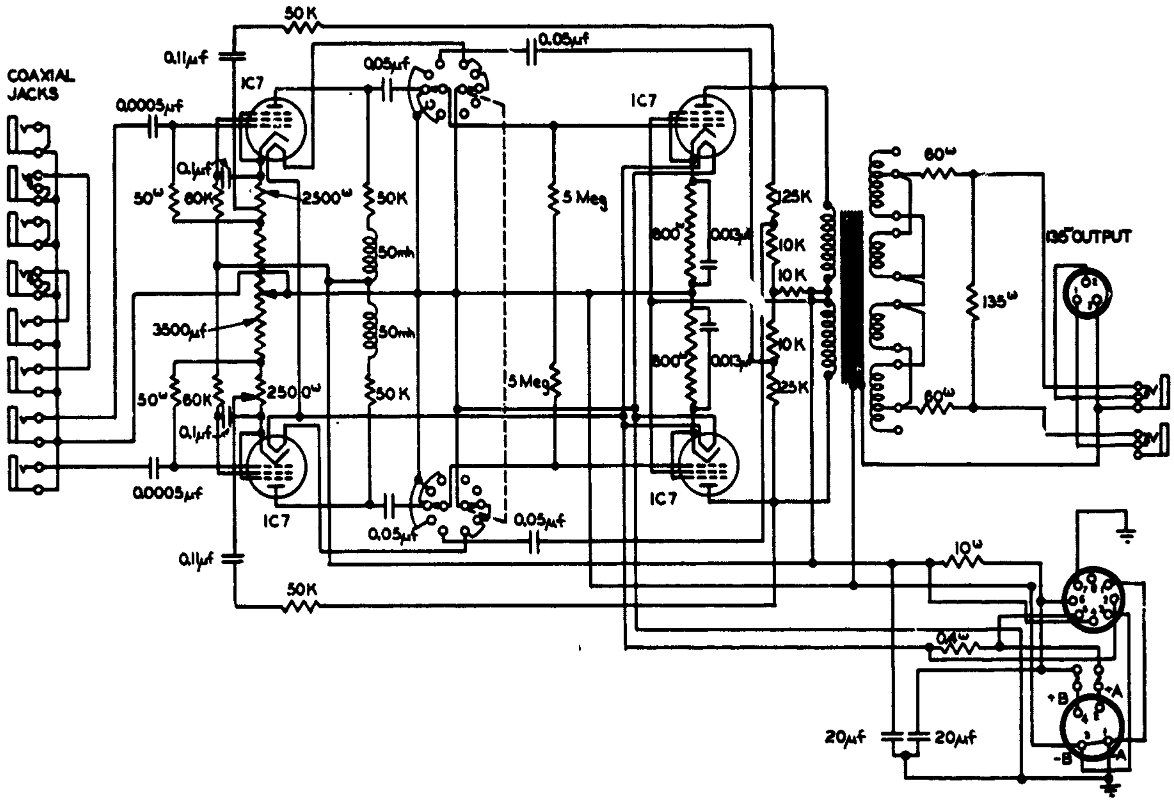


FIGURE 12. Circuit schematic of coupling amplifier. This amplifier provides extremely high input impedances for operation in balanced or unbalanced circuits.

Design considerations in the construction of these required the selection of a mid-frequency of 97 kc. The detector tuning oscillator of the signal generator of system 2, therefore, supplies a frequency of 747 kc. A rotary switch permits the rapid selection of any of the three band-pass filters, which have widths of 10, 300, and 6,000 c, centered at 97 kc. Following the filter circuits are three stages of amplification terminating in a 135-ohm output circuit.

Monitor Converter

System 2 is provided with a converter circuit comprising a modulator and a local oscillator which may be varied continuously from 94 to 100 kc. The primary function of this circuit is to permit aural monitoring of supersonic frequencies by converting the normal 97-kc signal output of the detector circuit, to an audio frequency range of 0 to 3,000 c.

Indicator

The use of narrow-band crystal filters in the detector circuit makes it necessary to center the output of the second modulator precisely on the mid-frequency. The adjustment of the detector-tuning oscillator to accomplish this is referred to as "tuning the detector" and it is correct when maximum detector output is obtained. It has been found expedient to provide for a continuous visual indication of this adjustment.

This indication is produced by taking a portion of the detector output signal from a constant voltage source in the recorder circuit and modulating it with a signal from a crystal-controlled oscillator tuned to the mid-frequency of the crystal filter in the detector circuit. The resultant difference signal is rectified and impressed on an electron-ray tube. The shadow angle of this tube opens and closes at the difference frequency. This is a direct indication of the deviation in cycles per second from the center frequency of the crystal filter. The tuning adjustment may thus be maintained within a fraction of a cycle at all times. Frequency drifts of the oscillator with respect to the filters are minimized by the use of oscillator-stabilizing crystals having the same temperature characteris-

tics as those in the detector circuit.

The continuous indication of tuning is essential, particularly for frequency response measurements at distances greater than about 3 meters. For such a length of path through water there is a significant delay in transmission. In order that the detector be tuned correctly for the incoming signal, it must lag behind the oscillator by an amount which is a function of the frequency sweep rate and the travel time of the sound through the water. The tuning indicator, which gives a continuous reading, permits compensating adjustments to be made during the test period.

Linear Level Recorder

Electromechanical recorders are used with each of the systems to provide continuous and permanent records of the response of the devices under examination. Each recorder consists of an amplifier which maintains an arbitrary equilibrium voltage at its output terminals by controlling, through a motor drive, the position of a sliding contactor on a strip attenuator at the input. A pen attached to this contactor records its position on a strip of moving paper. The speed of the paper drive is synchronized with the frequency sweep of the oscillator, so that the paper may have a fixed frequency scale.

The electronic circuit of the level recorder used with system 1 includes a special strip attenuator, a second attenuator for presetting the gain, and an amplifier tuned to 28 kc, followed by a half-wave rectifier circuit. The normal d-c output of this circuit is about 100 volts at equilibrium and is impressed on the grids of a pair of d-c amplifiers. These isolate the a-c thyratrons which follow. The anode current of each thyratron is passed through one of the windings of a small dual armature motor, the field of which is a permanent magnet. The thyratron and the d-c amplifier circuits are so arranged that an increase in the d-c voltage decreases the normally negative grid voltage of one thyratron with respect to its cathode, causing it to fire (allow the passage of current) and thereby drive the motor in one direction. Conversely, a decrease in the d-c voltage produces the same effect on the second thyratron, causing it to drive the motor in the opposite direction.

A continuous silk cord, after a few turns around the motor shaft, runs over three pulleys and back to the shaft. The pulleys are so placed that a section of the cord extends the length of the attenuator strip and parallel to it. On guides, also parallel, is mounted a carriage with an arm, making contact on the strip. This carriage is clamped to the cord so the contact may be moved to any point on the attenuator by the rotation of the motor.

The recorder seeks at all times to maintain the equilibrium d-c voltage at which the thyratrons are extinguished, by changing the setting of the contact on the input attenuator strip. The maximum rate at which the recorder can respond to changes in impressed level is approximately 100 db per second.

The resolution of this system is determined by the marginal d-c bias on the thyratrons and may be adjusted to within less than 0.1 db. The effective overall stiffness of the electronic and mechanical system in the region of balance is determined largely by an injected a-c bias, used primarily to control overshooting.

The strip attenuators are wound for a total attenuation of 50 db at 5 db per inch. They are mounted horizontally, directly over the recording paper which is a continuous strip with perforations along each edge. The paper moves over a roller with matching sprocket teeth that is driven by a small synchronous motor through an adjustable gear train allowing rates of 2, 6, or 18 inches per minute or per hour. A friction clutch with a double ratchet attachment permits the paper to be advanced or rewound on the supply spool by means of a hand crank. The paper drive motor is tied in to the oscillator drive motor so that both may be operated by a single switch.

The frequency resolution of the recorder is a function of the frequency sweep rate of the oscillator and the speed at which the recording paper travels. Normally, the oscillator and recorder are driven at the same relative speed (usually the intermediate one) to maintain the proper relationship between oscillator frequency and the frequency calibration of the paper. Under these conditions the individual charts for 0 to 150 kc are approximately 32 inches long. However, the frequency resolution may be improved ninefold by setting the oscillator sweep rate at minimum and the paper drive at maximum. The system is operated most frequently in this manner from 0 to 460 c with special recording paper. To cover this frequency range requires a chart 32.5 inches long.

The level recorder of system 2 differs from that of system 1 chiefly in that its amplifier is designed for a flat frequency response from 100 c to 150 kc, and in

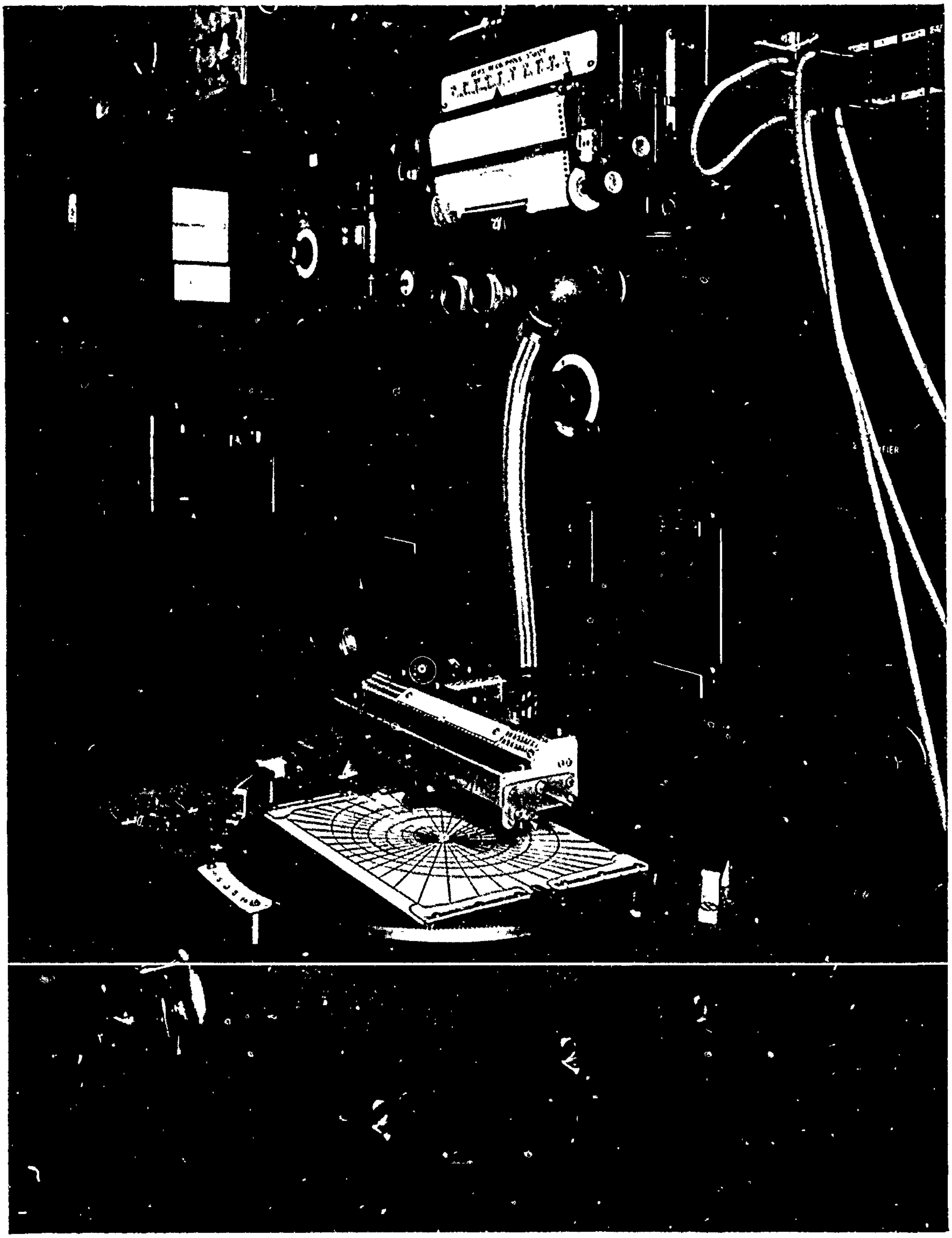


FIGURE 13. Polar recorder in use with System 2.

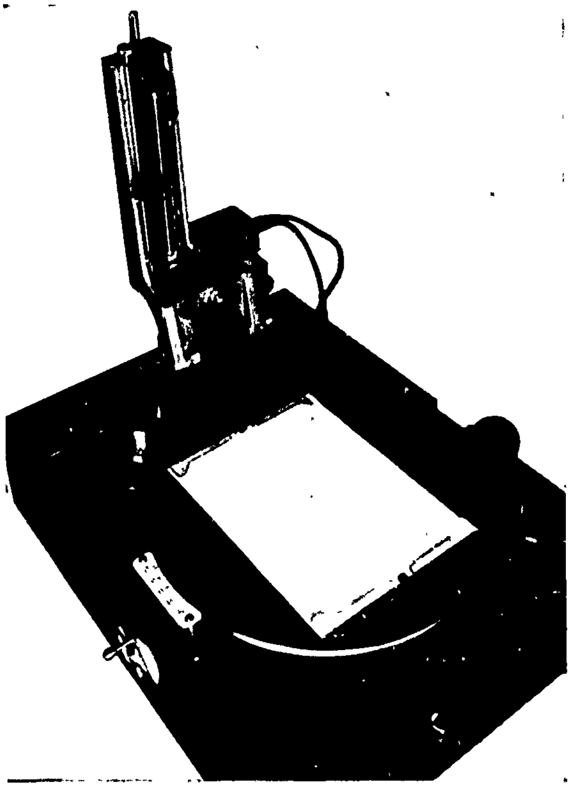


FIGURE 14. Polar recorder turntable assembly with recorder arm raised.

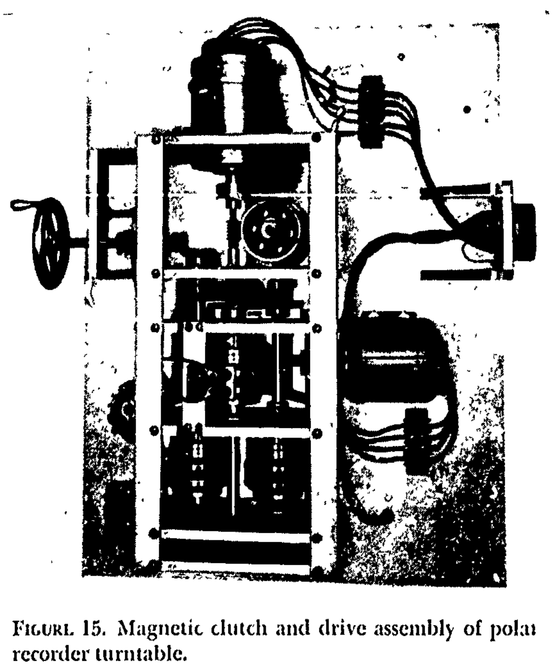


FIGURE 15. Magnetic clutch and drive assembly of polar recorder turntable.

the use of a full-wave rectifier, operating on a square law characteristic over a level range of some 9 db. These points of difference permit the recorder to be used for energy measurements of wide-band complex wave signals such as noise.

Polar Level Recorder

It is often desirable to know the response of an instrument for various directions of projection or reception, and auxiliary apparatus for this purpose is provided for both systems. It involves a rotator on which the instrument is mounted and a recorder in polar coordinates. It is evident that these must rotate in exact synchronism for the record to be correctly interpreted. Figures 13 and 14 show the turntable assembly of the polar recorder for system 2, and Figure 15, the driving mechanism and motor. The turntable has suitable positioning and holding devices for 8½x11-inch sheets of polar coordinate paper. The gear train and several electromagnetic clutches allow rotation of the turntable in either direction at an angular rate of 1, ⅓, or ⅑ rpm, both direction and rate being selected by switches. A 5F synchro is mounted on the end of the drive shaft, which thus couples it to the turntable through a 60:1 worm gear. This synchro is the director of a 5CT synchro attached to the rotator carrying the acoustic unit being tested. Whenever the angular position of this synchro does not correspond with that of the director, it generates error signals which are impressed on a thyratron servo amplifier. The altered output of the amplifier at once modifies the speed of the ¼ hp d-c motor driving the rotator and thus keeps the turntable and rotator in nearly the same angular position. The error signal is about 1 volt for each degree of angular difference and is thus a measure of the lack of synchronization which, with proper adjustment, should be less than 0.1 of a degree. A hand crank permits angular positioning of the turntable independent of the motor drive. As shown in Figure 15, the turntable may be set readily with the hand wheel, if it is disconnected from the driving motor by the release of the clutches. This allows it to be set to any desired relation to the rotator, if the circuit between the synchros is open. The strip attenuator, the sliding contactor, penholder assembly, and a dual armature motor are mounted on a tilt arm pivoted in such a manner that it may be lowered into position over the turntable (see Figure 14). The strip attenuator has been wound at 10 db per inch to a total of 50 db, the

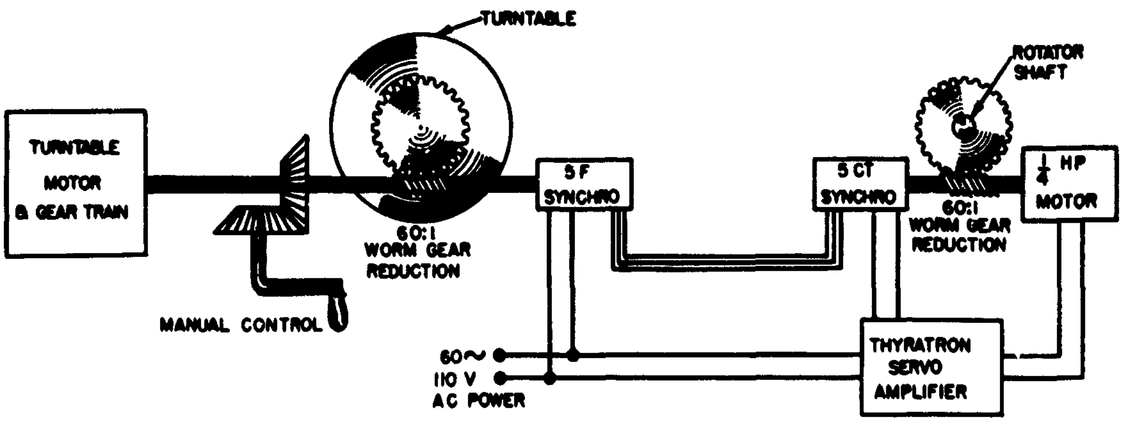


FIGURE 16. Schematic of polar recorder servo system. The 5F synchro coupled to the turntable is the director. The thyratron servo amplifier controlled by the 5CT synchro furnishes the power for the ¼-hp rotator drive motor.

usual range plotted. Plug-terminated patch cords are used in establishing connections to the electronic circuit and the required power supplies.

Operation of Pulse System

The pulse system is made up of a pulse generator, transmitter modulator, and a receiver modulator and pulse rectifier which were designed and built by USRL. When used with the 15-c to 150-kc system, acoustic pulses 0.1 to 30 milliseconds in duration may be produced and recorded. The use of the units is illustrated in Figure 17. A continuous single-frequency signal is applied to the input of the transmitter modulator, which acts as a "gating circuit." The output of the transmitter modulator is a pulse, that is, a limited train of constant amplitude waves of the signal frequency. The length and recurrence rate of these pulses are controlled by the pulse generator. They may be observed and checked on a cathode-ray oscilloscope connected across the output of the modulator. After checking, they are amplified and applied through the appropriate connection to the underwater transducer that is serving as a sound source or projector. The nature of the resulting acoustic signal depends, of course, on the electro-acoustic properties of the transducer.

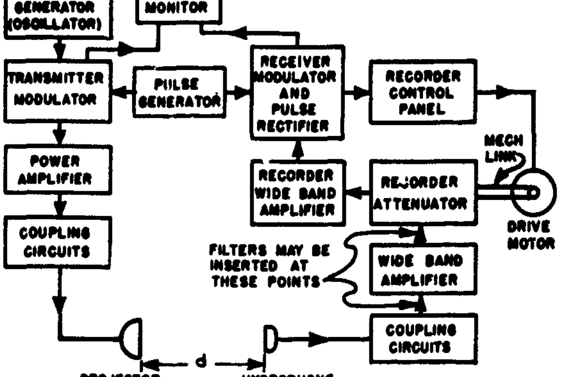


FIGURE 17. Block diagram of System 2 arranged for pulse measurements.

The acoustic signal generates in the hydrophone an electric signal that is amplified and applied to the linear or polar recorder attenuator as desired. After further amplification, the signal is passed through the receiver modulator, which is another gating circuit similar to the transmitter modulator. The receiving time can be controlled by the pulse generator in such a manner that any portion of the received signal may be accepted for measurement and the rest rejected. To aid in this adjustment, a cathode-ray oscilloscope is used to observe the incoming signal after it has passed through the receiver modulator. A switch permits the direct comparison of the total signal with the portion accepted for measurement. This plan allows the elimination of reflections which would be present in continuous-wave measurements and would result in an erroneous signal level.

If the pulses occur at the rate of 15 per second or more, the pulse rectifier produces a d-c voltage that is suitable for controlling the recorder circuit.

Units of the Pulsing System

Pulse Generator. The generator produces the pulses governing the action of the transmitter and receiver modulators. It consists of three unbalanced multivibrators, A, B, and C, that will produce

negative rectangular pulses when triggered. In addition, there is a relaxation oscillator capable of being synchronized with various subharmonics of the 60-c filament supply. Short, sharp, positive impulses from this oscillator are used to trigger stages A and B simultaneously. The rectangular pulse from A controls the transmitter modulator, and its length determines the length of the modulator signal.

The negative rectangular pulse from B is differentiated, yielding a sharp negative impulse at the beginning and a sharp positive impulse at the end. Multivibrator C is triggered by the latter (C responds only to positive impulses) after A and B are triggered and at a time determined by the length of the rectangular pulse from stage B. The rectangular pulse now generated in stage C is used to control the active receiving time of the receiver modulator.

The recurrence rate of this sequence can be set at 60, 30, 15, or 3 times per second by means of a selector switch. The pulse length of the multivibrators is controlled by the time constants of the associated resistance-capacitance [RC] circuits. Each stage has two such controls. A calibrated smooth change of resistance covers a time ratio of 20, and three fixed condensers give three decades of pulse length. With this arrangement it is possible to cover pulse durations from 0.1 to 30 milliseconds with overlapping scales for the whole range.

Transmitter Modulator. The transmitter modulator is essentially a stage of push-pull amplification with a cathode resistor which serves also as the cathode resistor of a 6L6 tube. The voltage drop across this resistor, due to the current drain of the 6L6, is made sufficient to bias the amplifying tubes of the push-pull stage beyond cutoff and thus keep them from passing any signal. The surge from the generator is amplified, and the resulting large negative pulse is applied to the grid of the 6L6, which stops conducting and allows the push-pull amplification to act normally for the pulse period. An output transformer is used with this push-pull stage in order to eliminate the d-c components owing to the amplifying tubes passing from a nonconducting to a conducting state and back again during the pulsing sequence. These components may be observed on a cathode-ray oscilloscope when there is no signal frequency being amplified. They are balanced by adjusting the screen-grid potentials of the amplifying tubes. An output transformer is used that has an essentially flat frequency characteristic from 1 to 150 kc.

The transmitter modulator has input and output impedances of 135 ohms. It operates from a d-c B supply of 275 volts and an a-c filament supply of 6.3 volts. The gain of the unit is 10 db and the maximum undistorted power output is 145 db vs 10^{-16} watt. The power output between pulses is more than 70 db below the maximum undistorted pulse output. The transients due to imperfect d-c balance are 50 db below the same maximum.

Receiver Modulator and Pulse Rectifier. The operation of the modulator section of the receiver modulator and pulse rectifier unit is very similar to that of the transmitter modulator but the operational characteristics are different. It has a high input impedance designed to work with the amplifier of the recorder circuit. It is capable of discriminating against the highest signal output of the cathode-follower stage in the preceding amplifier. Hence, any portion of the incoming signal may be selected without interference from the rest of the signal. This selection is controlled by adjustments on the pulse generator.

The conversion of the recurrent pulses from the modulator into a d-c voltage suitable for operating the power level recorder is not simple. This voltage produced must satisfy two requirements:

1. Its a-c component must be smaller than the change in the d-c voltage inherent in the resolution of the recorder. In other words, its magnitude will determine the resolution obtainable without appreciable instability, though the final limit is set by the nature of the recorder circuit.

2. It must be capable of changing about its equilibrium value at least as fast as the pen-drive motor can change the level of the signal into the pulse rectifier. If this condition is not met the recorder system will hunt, though this may always be avoided by decreasing the motor speed.

The circuit producing the voltage which meets these requirements is shown schematically in Figure 18. The operation is as follows: The receiver modulator is adjusted to pass a short pulse (0.3 to 0.6 millisecond) of the acoustic signal to be measured. This input to the pulse rectifier at point a and the resultant rectified voltage at point b are indicated on the drawing. The condenser C is made small (0.005 μf) in order that it may be charged to full value within the duration of the pulse. The resistor R is chosen so that 1/RC is approximately equal to the pulse repetition frequency. This allows the condenser to

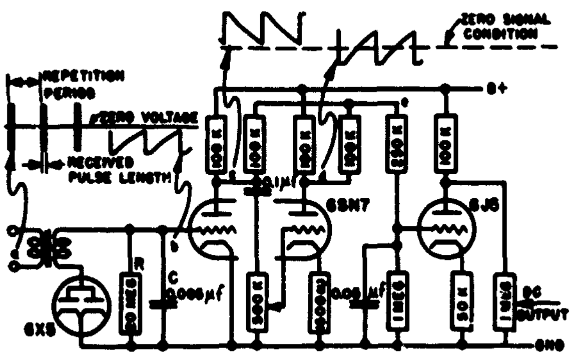


FIGURE 18. Circuit schematic of the pulse rectifier. The voltage wave form of the pulse is indicated at various points in the circuit.

become almost wholly discharged between pulses. Hence, the grid signal is a saw-tooth wave, the amplitude of which can change rapidly with change in the incoming pulse.

The first section of the 6SN7 acts as an impedance changer and phase inverter, the voltage at point c still containing the d-c and a-c components of the rectified signal at b. The a-c component of this voltage is applied to the grid of the second section of the 6SN7 through the RC network. The time constant of this RC combination should be approximately equal to that of the filter section. By proper adjustment, the signal at d can be made equal to the a-c component of the signal at c, but inverted in phase so that the mixed voltage at e will be approximately equal to one-half the d-c component of the voltage at c with the a-c components balanced out. To facilitate this adjustment, a terminal is supplied for observation with a cathode-ray oscilloscope.

An increase in the intensity of the received acoustic signal causes the d-c voltage at e to rise. The thyratron control circuit used with the pulse system requires, however, a decrease in the d-c voltage with increase in signal intensity and, for this reason, the final tube shown is used.

In order to be used with the pulse system, one of the thyratron control circuits is modified and a single coaxial jack installed to take the d-c output of the pulse rectifier. A switch on the front of the panel allows the operator to choose the output of either the recorder circuit or the pulse rectifier. When the latter is chosen, 50-ohm resistors are automatically inserted to slow the pen-drive so that the recorder will not hunt. This reduces the speed of the recorder from 100 to some 30 db per second.

A gain control at the input of the receiver modulator allows the sensitivity of the pulse recording system to be made equal to that of the usual continuous-wave system. However, the sensitivity of the pulse system is somewhat dependent on the length of the received pulse and the repetition rate. In nearly all tests, however, the values of these variables will be chosen and held constant throughout.

The frequency response of the receiver modulator and pulse rectifier is flat within ±0.5 db from 1 to 120 kc. The response at the low-frequency end is controlled largely by the number of cycles of the signal within the pulse being measured.

MISCELLANEOUS FEATURES, AUXILIARY APPARATUS

Methods of Connecting. Great flexibility of interconnection is obtained by the use of jack fields as terminals for the individual pieces of electric apparatus mounted in the bays. The arrangement of the jacks within the field is based on factors such as accessibility, convenience in wiring, and the consideration of cross talk. Many jacks are interconnected so that commonly used combinations of apparatus are established without the use of external connectors. The jack fields also provide terminals for inter-bay, inter-system, and system-to-pier lines, and for frequently used coils, attenuator pads, and load resistors.

Connections between jacks are made with plug-terminated, flexible, shielded cords referred to as patch cords. Where the jack grouping permits, connection between adjacent jacks is made with short-circuited cordless plugs. The types of patch cords and plugs may be seen in Figures 9 and 10.

Grounding. Each system is provided with a fundamental circuit ground comprising a copper pipe driven into the lake bottom adjacent to the pier testing area. Four No. 0000 stranded copper cables connect each fundamental ground to heavy copper bus bars in the pier booths and apparatus bays, and to copper strips mounted along the test areas which are used for grounding test apparatus. Individual circuit ground connections are made directly from the bus bars to all panel-mounted equipment. The lead sheath and outer conductors of the coaxial transmission lines between the pier booths and the laboratory are grounded at the jacks in the pier booths. The types of ground are indicated on the jack fields by means of colored celluloid windows placed over the designation strips.

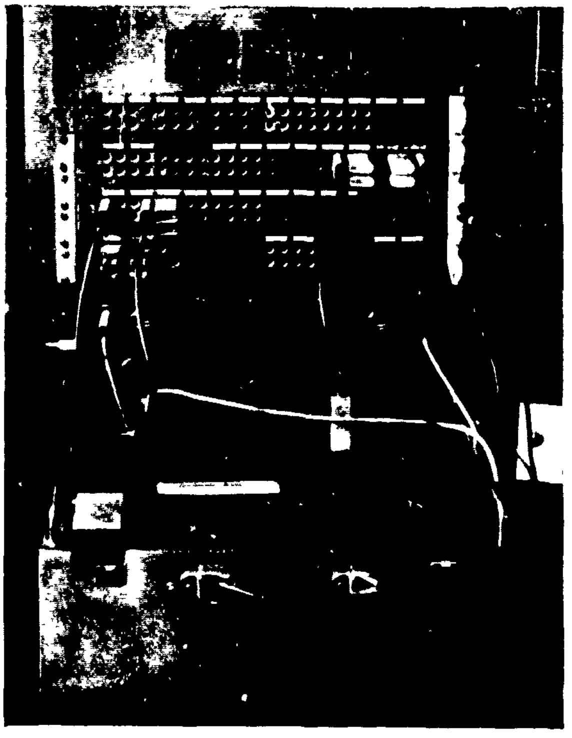


FIGURE 19. 30A transmission measuring set connected in system jack field.

Transmission Measuring Set. The standard instrument adopted for power level measurements is a Western Electric 30A transmission measuring set. The essential elements are a thermocouple, indicating meter, attenuators, and switching circuits. The input impedance is 135 ohms and the set operates at frequencies up to 150 kc. The readings may be varied in increments of 1 db through a range of 90 db by means of attenuator sections connected by dials and switches. A high degree of convenience has been obtained by the use of jack terminations for the individual circuit elements. The circuit of the instrument provides for both gain and loss comparison paths, selected by a switching key.

The meter scale covers a range from -10 to $+3$ db on either side of a center zero. The design is such that the zero reading means a power level of 130 db vs 10^{-16} watt (1 milliwatt). An internal d-c circuit provides for the maintenance of the thermocouple and metering circuit calibration. Recalibration of the metering circuit may be necessitated by thermocouple aging, temperature changes, and thermocouple replacements. The overall accuracy of the transmission measuring set is ± 0.1 db.

Monitor Amplifiers and Speakers. Each system is provided with means for listening to the received signal. System 1 has an audio-amplifier with a maximum gain of about 60 db and an output power of some 12 watts. This amplifier is used in conjunction with a dynamic speaker. System 2 is equipped with a monitor converter circuit that allows the use of earphones at the output of the detector circuit. The monitor output signal may also be sent through permanently installed lines to the power amplifier and loud-speaker of the reproducer set.

Reproducer Set. A transcriber is provided for reproducing, electrically and acoustically, for calibration purposes, various types of water noises including a number of ship noises. The transcriber has two separate turntables, each with a reproducer for vertical or lateral cut records at 33⅓ or 78 rpm. A preamplifier associated with each head permits individual control of level and of frequency weighting characteristics. A 50-watt power amplifier is used for the operation of a high-quality speaker. The frequency response of the amplifier without equalization is substantially flat from 30 to 10,000 c.

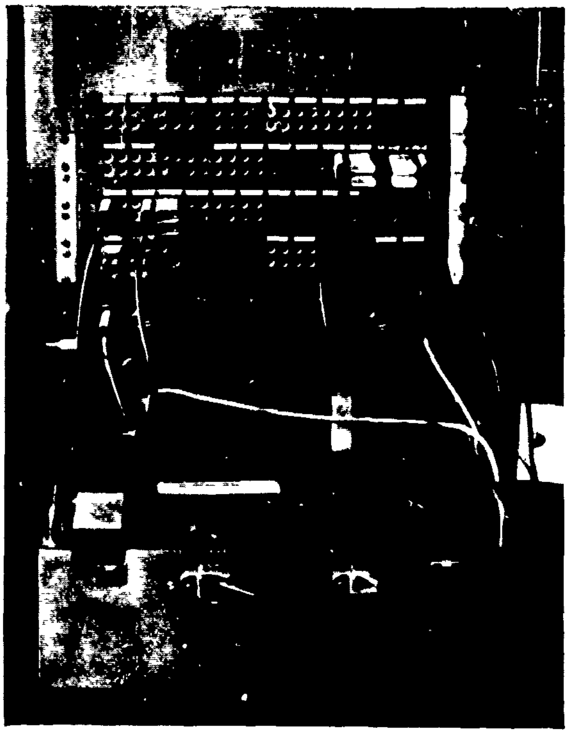
High-Pass and Low-Pass Filters. A number of high- and low-pass 600-ohm filters have been assembled and connected through suitable switches so that single units or combinations may be used. The high-pass filters have cutoff frequencies of 0.2, 0.7, 2, 15, 33, and 60 kc; the low-pass filters, 0.7, 2, 5, 15, 35, 70, and 150 kc. All filters have attenuation beyond the cutoff frequencies of more than 50 db.

Laboratory Intercommunication Systems. Each test system has microphone-speaker communication between the laboratory and the piers. It has been arranged so that it is possible to contact each pier from any one of the systems and vice versa. This intercommunication is required to permit proper coordination between the operators at separate locations while making calibration measurements.

MECHANICAL FEATURES OF OUTDOOR FACILITIES

Handling Facilities. Overhead monorails are provided for trolleys to which chain hoists are attached. Rail switches permit the placing of hoists carrying rigged apparatus on storage spurs or in any arrangement desired for testing. The hoists have capacities up to 1 ton, and the rail height permits a lift above the piers of 16 feet.

Suspension Members. Standard laboratory hydrophones and small test devices are usually rigged on



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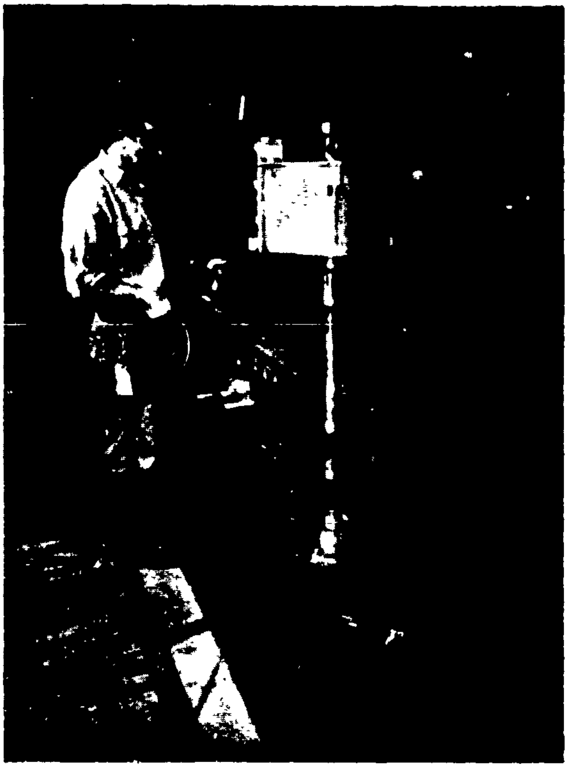


FIGURE 23. Rotator and suspension framework.

FIGURE 24. Placing rotator in position in carriage.

engage the driving motor, and a control for each projects through the housing. Each shaft has a 5CT synchro coupled to it through a 60:1 gear train. The synchros are mounted in an auxiliary housing on the side opposite the clutch controls. The driving motor rests on top of the gear box and is coupled to the internal gear train through an assembly that provides for manual operation by a crank.

The concentric shafts are approximately 3 feet long. The outer one, a 3-inch tube, terminates in a metal framework, adjustable in length. The inner one is extended by a 1-inch pipe of adjustable length, which is terminated in a 4-inch flange, and is centered with the bottom plate of the outer shaft assembly. The approximate load capacity of the rotator is 1,000 pounds per shaft.

Mounting Fixtures. Universal mounting fixtures and others of special application are used for attaching test transducers to the various suspension members. Examples of these fixtures are shown in Figures 20A and 20B, which illustrate the devices for 1A and 3A hydrophones. Figure 20C shows a fixture used for rigging a variety of small and medium size transducers.

Carriages. The carriages that are used to support the suspension members roll across the test areas on flanged wheels fitted with brakes and matched to the side rails. An H-type carriage, shown in the foreground of Figure 25, is used for supporting transducers that do not require rotation. A turret type is shown in Figures 22 and 26. The upper assembly may be rotated at $\frac{1}{6}$ rpm by a small synchronous motor acting through reducing gears and a rubber friction wheel. Studs attached to the underside at 30-degree intervals operate a microswitch to indicate at a remote point the angular position of the turret. However, because of the superior facilities provided by the rotator, the turret type is now used only for medium and heavyweight instruments not requiring steady rotation.

A special carriage is used for the rotator assembly with the housing resting on a flat bedplate. A split radial thrust bearing on the underside engages the 3-inch outer shaft and adds to the rigidity of the system. Two lever-operated brakes secure the carriage at any position.

Screens. Screens are used frequently to minimize standing waves resulting from surface and bottom

FIGURE 25. Determining the testing distance between transducers. Rotator shown at far end of test area is mounted on "H" type carriage.

FIGURE 26. Typical test arrangement using turret type carriage. Portable coupling amplifier in foreground.

reflections.[b] The most common screens are thin-walled watertight metal envelopes about 2 by 1 feet by 1 inch containing a sheet of hard felt. Flanges along the 2-foot edges permit the assembly of several screens in multiple-unit configurations. Figure 27 shows a V assembly being placed in position to function as a surface screen, that is, to reduce surface reflections from the region between a projector and a hydrophone. Similar assemblies are sometimes placed below the acoustic axis of transmission with the V inverted to minimize bottom reflections.

Special Facilities. Compressed air is generally available from an outlet and special filter in the transmission booth of pier 1. This installation is primarily for charging the reservoirs of 4A- and 4B-type low-frequency projectors. Other general uses include cleaning and drying the less accessible parts of miscellaneous gear with air blasts.

A portable gear pump delivering about 10 gallons per minute and driven by a reversible motor is provided for use on the piers. A long connecting shaft allows the pump to be immersed in the lake, thus providing a water supply free from air. The pump is used for washing and debubbling test transducers and for filling and emptying domes not provided with drain plugs.

An underwater lamp and a viewing device are available for examining transducers and their rigging in test positions.

[b] A general discussion of screens, from a theoretical standpoint, is given in Chapter 4.

A portable box of wrenches, screwdrivers, pliers, and other tools used for rigging is maintained at each pier. A complete supply of rules, graduated steel tapes, levels, and general marine hardware is available for measurements and rigging.

Maintenance of Performance

Safety Precautions. Units having dangerously high voltages are equipped with safety switches which must be opened before access to the unit is made. This is accomplished by an interlocking mechanism, which must be checked frequently for correct operation.

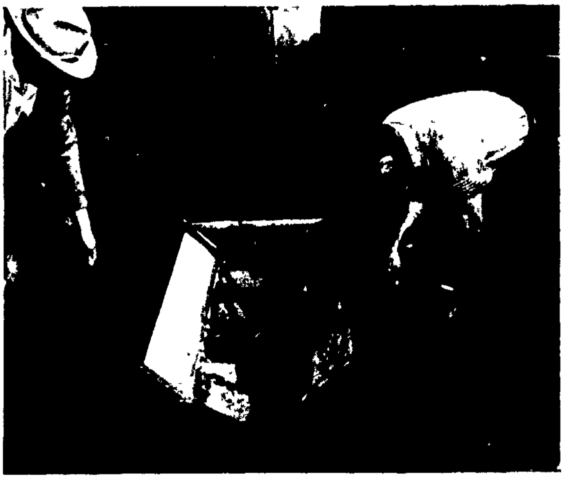


FIGURE 27. Lowering the "V" screen into position for reducing surface reflections.

No one is allowed to work on a pier alone when weather conditions are hazardous.

Electrical. The power is turned on about 3 hours before any measurements are made so that thermal equilibrium is reached to minimize any drift in frequency or level. Check observations are always made at the beginning of each day and, if necessary, repeated at intervals. The performance of each regulated rectifier is checked by means of a built-in metering circuit, which permits the observation of output voltage and load current distribution among various tubes. This is required frequently as faulty tubes result in a nonuniform load distribution.

The calibration of the 30A transmission measuring set is described earlier in this section.

The signal generator is adjusted for continuous-wave, noise, pulse, or other types of tests.

The wide-band receiving amplifier, detector, and recorder are checked as a unit. Individual circuits are tested only when the unit fails. To observe the overall performance and adjust the sensitivity, the oscillator is set at 10 kc and adjusted to 130 db vs 10^{-16} watt with the 30A set. The signal is fed through the wide-band amplifier and the detector with zero gain, and the recorder is adjusted to the same level entering the amplifier.

The resolution, stiffness, and over-shoot of the recorder are adjusted and the rate of response to changing levels observed. Any substance that increases the friction between the sliding surfaces reduces the response rate and may soon cause serious wear.

The carrier frequency can be balanced out at the first modulator of the detector circuit with the signal generator set at 0 c. The controls for balancing the rejection circuit are adjusted until the recorder signal is at a minimum.

In addition to these individual adjustments, it is desirable to determine the overall gain of the test system. The circuit and the levels used are shown in Figure 28. A level of 160 db vs 10^{-16} watt is established at the projector side of the impedance matching coil with the 30A set connected to this coil through a 20-db matching pad. The oscillator and power amplifier gain controls are adjusted until the correct power level is indicated on the set. Then the oscillator frequency dial and recorder paper scale are synchronized at 0 c and a response is taken up to 150 kc. Since irregularities in the performance of any of the component parts will show up in the record, the system is considered to be in operating condition if

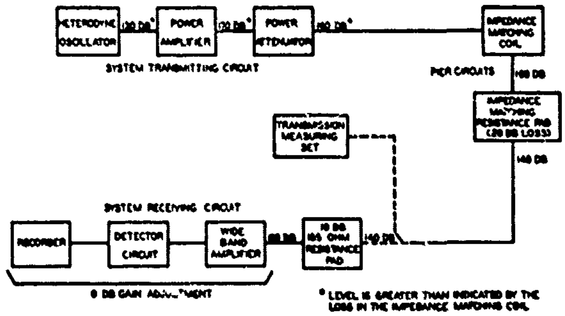


FIGURE 28. Arrangement for overall system check. Signal levels are given in decibels versus 10^{-16} watt.

the recorder curve is satisfactory in magnitude and flatness.

The test systems are completely overhauled after a year's use. All tubes are tested; patch cords are checked for continuity and leakage; coil and attenuator characteristics are measured. Transmission and leakage characteristics of all lines are checked. Poor leakage-to-ground in coaxial lines may result from foreign particles, and, if so, is usually corrected by discharging a 500-μf condenser at 200 volts over the path. After reassembly, individual circuits are checked and adjusted, if necessary.

Mechanical. It has been found advisable to establish certain routines in the maintenance of the mechanical equipment. Important groups of these are the following:

1. All electric contacts including plugs and jacks are cleaned at regular intervals to forestall troubles arising from dirt and corrosion. Rough or damaged surfaces are refinished or replaced.
2. The piers are examined periodically for settling by placing levels both on and across the rails, which were designed with bolts for adjustment.
3. The test equipment, especially that used outdoors, is protected from the weather as much as possible. This includes covering when not in use, keeping pier booths and windows closed, and draining or providing underwater storage for free-flooding devices.
4. All mechanical equipment, such as chain hoists, rigging fixtures, etc., is regularly inspected, lubricated, and stored under shelter during the winter.

6.2.2 Practical Calibration Procedure

COMPARISON TESTS

A large part of the calibration work done by USRL, particularly in the range from 15 c to 150 kc,

was comparison of instruments in a free field. Reference has been made in Chapter 5 to the advantages of this method, and it seems probable that it will continue to be an important one. The following discussion of testing procedures pertains to transducers in general, the distinction between hydrophones and projectors being made only when the nature of the device affects the techniques.

Required Background Information. In planning an efficient program, it has been found expedient to know in advance the size, shape, and other characteristics of each device. The most essential information is its actual performance. However, knowledge of the end application and of the operating principle permits emphasis to be placed on the characteristics of primary importance. The following illustrates the type of information to be included:

1. Physical Characteristics
   - Size of diaphragm
   - Location of diaphragm center
   - Location of center of rotation
   - Configuration and type of active elements
   - Position in use with and without auxiliary gear
   - Drawings showing dimensions and mounting details
   - Temperature and pressure limitations
2. Electrical Characteristics
   - Terminal impedances
   - Direct-current power requirements
   - Working and maximum power input for continuous-wave and for pulse operation
   - Tuning and associated network requirements
   - Circuit schematics
   - Frequency range

Ordinarily there are points of particular interest in each program. For example, it may be desired that special attention be given to a restricted portion of the frequency range, directivity patterns be taken about certain axes or at specific frequencies, a detailed investigation be made of the secondary or tertiary resonances of a sharply resonant device, or the performance of a projector be studied at specific power inputs.

Preparation for the tests may be expedited if all this information is furnished well in advance of the testing date. A person thoroughly familiar with the instrument under observation can be of material assistance in the testing program, and one should be present if possible.

Rigging. Throughout the rigging, every precaution is taken to protect the instrument from mechanical shock or other injury, and crystal devices that are injured by high temperatures should be shielded from the sun as much as possible. In many cases a large portion of the time is devoted to rigging the test devices and associated gear. Each device presents different rigging problems arising from disparities in weight, size, frequency range, and the type of tests planned. There are, however, many rigging considerations common to most testing programs, and these will be considered in the order in which they arise.

The types of suspension for positioning transducers are described in Section 6.2.1. The selection of a particular one is dependent on the physical characteristics of the instrument as well as on the nature of the observations to be made. In rigging for tests in which the response is wanted only at a few angular positions, a heavy instrument is mounted on 1-inch pipe, while a light one usually is mounted on a hydrophone rod. Since the rod is supported by gimbals and an antishock mounting, it requires symmetrical loading. In cases where the instrument construction does not allow this loading, the 1-inch pipe may be used or the device may be mounted on the rotator. When the pipe is used, it is clamped in position by blocks on rubber mountings. This protects against shock but does not provide a completely free suspension. In any case, care must be taken to have the whole assembly hang in a truly vertical line, particularly if the distance between instruments is measured after they are submerged. The test distance is taken to be that between the upper parts of the suspension rods, with corrections for the position of the transducers relative to these rods. Where the testing distance is short, small deviations from the vertical may result in appreciable errors. Such irregularities in hanging may also displace the instrument with respect to the acoustic axis of the standard instrument, introducing serious errors at frequencies where sharp beam patterns occur.

In rigging a test device to a pipe suspension, an attempt is made to have the center of gravity of the instrument lie on the major axis of the support and the plane of its active face parallel to the axis. Adjustment screws and small levels in the mounting blocks facilitate the process, and counterweights may also be employed. If the required adjustment is not too large,

the assembly may be leveled after immersion. The mounting of even the heaviest instruments on the rotator does not require leveling because of its rigidity.

Determination of Test Conditions. Before an instrument is finally positioned, the depth, testing distance, and electric coupling are determined in as close accord as possible with the principles set forth in Chapter 5. It is evident that the final setup will often be a compromise with ideal conditions.

The depth of the testing areas is about 6 meters, though most instruments are tested at 2 to 3 meters. The exact depth may be selected with the hydrophone rod and the pipe suspensions. The length of the hydrophone rod may be set approximately before immersion, and adjusted afterward by the lead screw. With the rotator, the adjustment of depth can only be made in rather large steps and with no change possible after immersion. This requires that the associated testing instruments be adjusted to operate with it, whatever its position.

Estimates of testing distance based on instrument size and frequency range are usually made before the tests, so that the pier location of the instruments may be tentatively determined. Several testing distances are commonly used to observe the effects of the bottom and surface reflections and of standing waves between the instruments. Projectors are usually faced away from the shore, to avoid first-order shore reflections.

When several projectors are mounted to calibrate a sound field over a wide frequency range, the higher frequency ones are mounted near the shore and directed toward open water, while the lower frequency devices are suspended at the far end of the pier and directed toward shore. The test hydrophone is mounted on the turret between the two projector assemblies. This arrangement permits the hydrophone to be positioned with respect to either projector. An alternative method involves mounting the two projectors back to back in the turret so that either may be quickly set into proper relation to the fixed hydrophone. Such an arrangement may be seen in Figure 22.

Usually the recommended electrical conditions are approximated as closely as possible. If the device is a projector, the recommended source impedance can usually be matched with an available coil. If it is a hydrophone, it may be connected directly to a high-impedance coupling amplifier or terminated in accordance with the recommended operating conditions.

Final Preparation for Testing. All too often the leads furnished are too short to permit testing at the proper depth. A number of single coaxial cables are available for extending such leads. Splices are made watertight by several layers of rubber tape or by the use of underwater junction boxes. The cable is then taped to the supporting rod and, in the case of heavy cable, wound about the rod to prevent asymmetrical loading.

Before any instrument is tested, it is thoroughly washed and debubbled, since significant errors may be introduced by air bubbles or films. The active surfaces are washed with a soft cloth soaked in a strong soap solution to which a generous supply of wetting agent has been added. This procedure removes oil, grease, or dirt particles which occlude air. The manner in which the water meniscus traverses the instrument face when it is lowered and raised in the water is a good criterion of cleanliness. The meniscus progresses smoothly and without breaks if the face is thoroughly wetted. A device having structural irregularities which may trap air on, or near, the face is carefully debubbled after it is submerged by an air-free stream of water from an underwater pump or hand syringe.

After an instrument has been rigged and thoroughly cleaned, it may still require soaking. This is necessary to reach thermal equilibrium for *x*-cut Rochelle salt crystals or others of high thermal inertia. Such instruments are suspended in the water for several hours before tests or even overnight, depending on the size of the device and the difference between air and water temperatures.

The resistance of the device and the insulation resistance between terminals and case are checked before submersion and during tests if leakage is suspected.

After the instruments are positioned and electric connections made, preliminary trials are made to detect extraneous noise, cross talk, or signs of overloading the hydrophone or receiving equipment. Excessive noise is easily heard. Many test devices used in salt water are not provided with electric shielding, and so pick up power-line frequency from ground currents. When grounding adjustments do not improve the signal-to-noise ratio sufficiently, it may be necessary to insert suitable rejection filters ahead of the wide-band receiving amplifier to prevent overload-

LOG

Mt. L. TEST STATION 1 SYSTEM; 1 PIER

PROJECT NO. 000 DATE 11-15-44 COPIES TO STATION FILE AND N. Y. OFFICE SHEET NO. H 1

INDEX: Run No.	Type	Color	Letter	Ref Oct	Time	WATER TEMP: Deg. C	Depth CM	TRANSMITTING: Proj Type-No	φ/θ	Pier Pos CM	Depth CM	Avail. Power: Zo	Level	FREQUENCY-KC: Single, Range, or Mid-Band	Band W'th: Tr.	Rec.	PULSE: Lgth-MS Tr.	Rec.	DT'g MS	Rate PPS	RATES: Sw'g	Pap'r IPM	Ro'n RPM	RECEIVING: Hydro Type-No.	φ/θ	Depth CM	Horiz Dist CM	Sys Gain db
1	R	V	A	I	11:00 AM	72°	250	6B-11	0°	100	226	135	150	25-100							m	6		1A13	0°	226	160	70
2	R	R	A	'	11:05	'	'	'	'	'	'	'	'	'							'	'		'	'	'	+90	70
3	CO	R	A	II	11:10	'	'	—	—	—	—	—	—	' '							f	18		'	—	'	—	10
4	CI	G	A	III	11:12	'	'	—	—	—	—	—	—	' '							'	'		—	—	—	—	10
5	R	G	B	IV	11:20	'		6B-11	0°	100	226	135	150	' '							m	6		3A-68	+90°	226	+60	30
6	R	V	B	'	11:25	'	'	'	'	'	'	'	'	' '							'	'		'	'	'	+90	30
7	R	G	C	V	11:40	'	'	'	'	'	'	'	'	' '							'	'		QCU-2	0/0°	'	+90	20
8	R	V	C	'	11:46	'	'	'	'	'	'	'	'	' '							'	'		'	'	'	+180	20
9	R	R	C	'	11:50	'	'	'	'	'	'	'	'	' '							'	'		'	'	'	+360	20
10	D	BK	D	'	12:05	'	'	'	'	'	'	'	'	24.19							/		1/3	'	[illegible]	'	+36[illegible]	—
11	R	V	E	VI	1:25	'	'	QCU-2	0/0°	700	'	135	160	15-85							m	6		3A68	+90°	'	+180	0
12	R	R	E	'	1:37	'	'	'	'	520	'	'	'	' '							'	'		'	'	'	+360	0
13	E	V	E	VII	1:40		'	'	—	'	'	'	'	' '							f	18		—	—	—	—	30
14	Σ	G	E	'	1:41	'	'	'	—	'	'	'	'	' '							'	'		—	—	—	—	—
15	Δ	BL	E	'	1:42	'	'	'	—	'	'	'	'	' '							'	'		—	—	—	—	—
16	I	R	E	'	1:43	'	'	'	—	'	'	'	'	' '							'	'		—	—	—	—	—
17	CO	R	C	VIII	1:50	–	–	—	—	—	—	—	—	10-40							'	'		Coup Rp[illegible]	—	—	—	20
18	CI	G	C	III	1:52	–	–	—	—	—	—	—	—	' '							'	'		' '	—	—	—	20
19	R	V	F	IX	3:10	7.2°	250	6B-11	0°	100	226	135	150	' '							m	6		QCU-2	0°/44°	-220	360	20
20	D	BK	G	'	3:20	'	'	'	'	'	'	'	'	24.20							/		1/3	'	[illegible]	'	'	—
21	D	BK	H	X	4:20	'	'	'	'	'	'	'	'	24.20							/		'	'	[illegible]	'	'	—
22	D	BK	I	XI	5:10	'	'	'	'	'	'	'	'	24.20							/		'	'	[illegible]	'	'	—
23	R	V	J	XII	6:05	'	'	'	'	'	'	'	'	10-40							m	6		QCU5	0°/0°	'	'	40

LOG(10-44) *R-RESPONSE; CI-CPL'G IN; CO-CPL'G OUT; D-PATTERN; IN-INH'NT NOISE; NA-NOISE AG'TAT'N; I-PROJ CUR; E-PROJ. V'LT; Δ & Σ-PROJ. PR.

FIGURE 29. Sample log sheet.

ing by the noise. Overloading of the preamplifier associated with the test hydrophone should be investigated, particularly in the case of devices having a high sensitivity. Overloading may be detected with a cathode-ray oscilloscope which shows a nonlinear relation between the input pressure and the output signal. The sound pressure on the hydrophone may be reduced by decreasing the driving power of the projector or by increasing the test distance.

Cross-talk levels may be investigated by spacing the projector and hydrophone about 3 meters and by adjusting the system gain controls to a high recorder level at some convenient frequency. A rapid change in frequency, effected by manual operation of the dial, should show an abrupt drop in the output signal because of the effective detuning action of the detector. The magnitude of this change is a direct measure of the margin between the acoustic signal and the electric interference.

Test Observations. The recorder charts of runs for acoustical and electrical data are supplemented by detailed log and circuit sheets giving an index to the series of tests, identifying the various runs, and noting the instruments used and the circuit arrangements. To facilitate the recording and analysis of the data, each run is numbered according to the test sequence, and each chart is given an identifying letter. Other entries on the log sheets include the water temperature, testing depth, pier positions of the instruments, and the time at which each run is taken. Sample log and circuit sheets are shown in Figures 29, 30, and 31. In addition to the data, descriptions of the test devices are included in the form of blueprints and schematics furnished by the maker of the apparatus, rough sketches made at the laboratory, or photographs.

Test observations are usually made to calibrate a sound field with a standard hydrophone, to calibrate

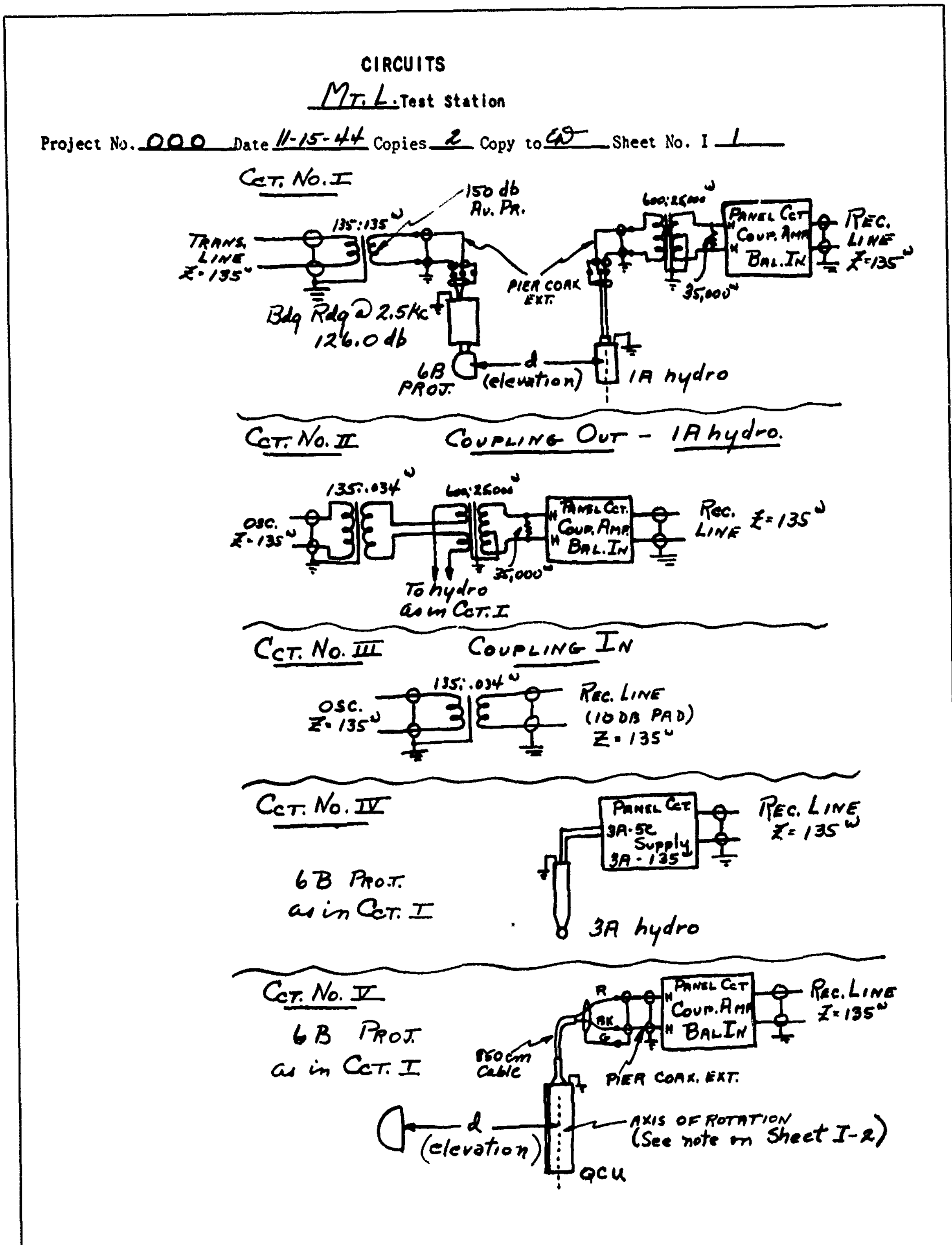
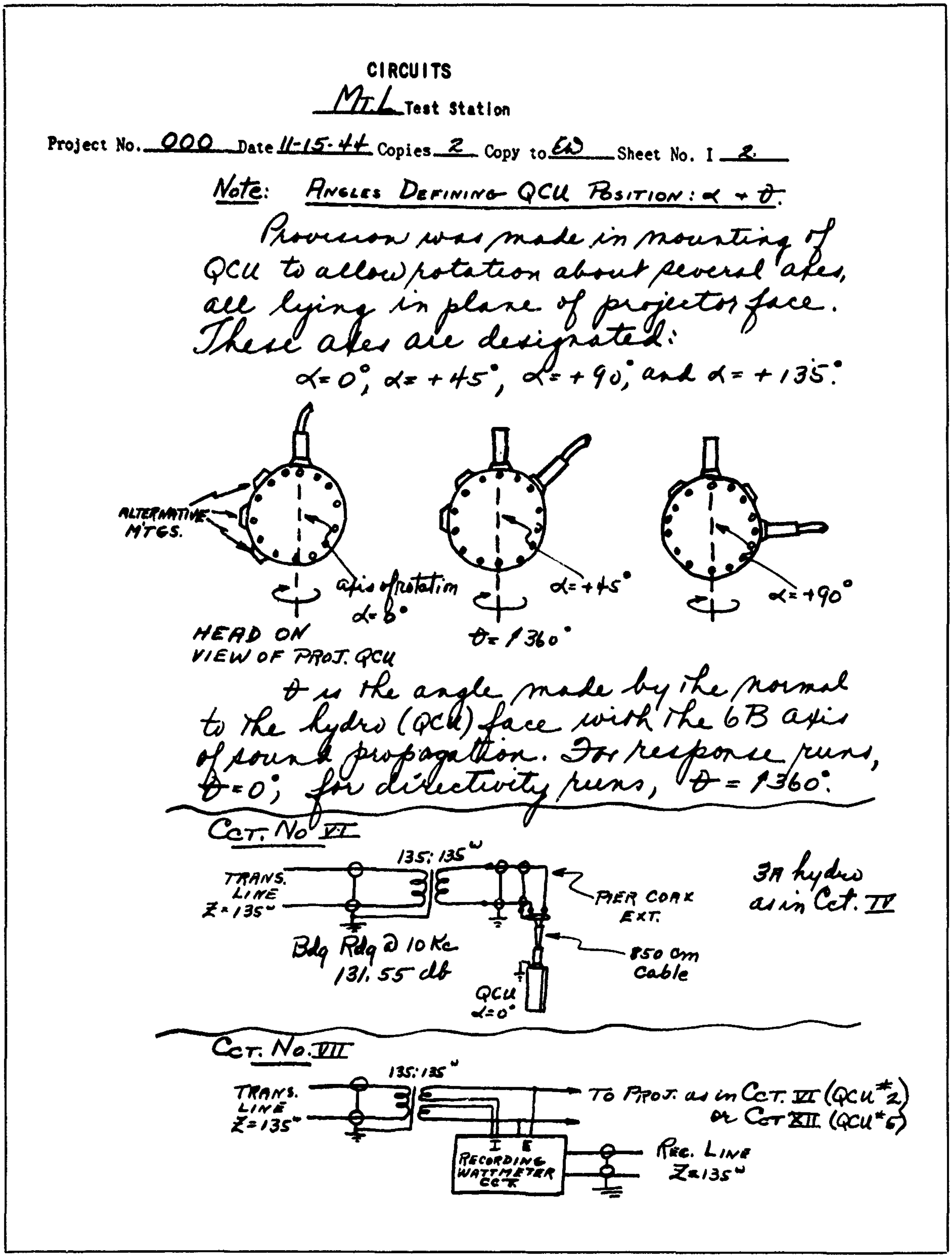


Figure 30. Sample circuit sheet No. I-1.



CIRCUITS

MtL Test Station

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Note: Angles Defining QCU Position: α + θ.

Provision was made in mounting of QCU to allow rotation about several axes, all lying in plane of projector face. These axes are designated:

$\alpha = 0°$, $\alpha = +45°$, $\alpha = +90°$ and $\alpha = +135°$.

θ is the angle made by the normal to the hydro (QCU) face with the 6B axis of sound propagation. For response runs, $\theta = 0°$; for directivity runs, $\theta = 1360°$.

Cct. No VI

Cct. No. VII

FIGURE 31. Sample circuit sheet No. 1-2.

transducers functioning primarily as hydrophones, and to calibrate transducers designed to function primarily as projectors. Reversible transducers are calibrated functioning in each capacity.

Reference data from the first procedure are required only when the test transducer is to be calibrated as a hydrophone. These runs generally precede observations on the test instruments and are repeated, in part at least, once each day during the test period.

Reference Data. When a device is to be calibrated as a hydrophone, one or more standard projectors are selected to cover the frequency range of the test instrument and the sound field established by each of them is calibrated by at least two standard hydrophones. One of the hydrophones should have directional characteristics which will discriminate against surface and bottom reflections, though reflective effects may be decreased by operating at short distances within the limits discussed in Chapter 5. Whenever certain frequencies are of particular interest, as in the case of sharply resonant devices, it is advisable to choose standard hydrophones having minimum irregularities of response at these frequencies.

Before reference runs are made, the angular position of each projector is set where the maximum acoustic output appears on the recorder. This training is done at a frequency where the beam pattern of the projector is sharp, and at a distance sufficient to minimize the effect of standing wave patterns between transducers. With low-frequency projectors, the beams are usually broad enough so that careful mechanical alignment in rigging is adequate. Once adjusted, each projector remains undisturbed throughout the tests.

Runs are taken at several distances and agreement between the computed and observed distance losses indicates the absence of significant standing waves or reflections. The sound field of each projector is then computed at several frequencies, from the data obtained with each standard hydrophone. With random deviation from the mean, agreement within 1 db is reasonable assurance of projector and hydrophone stability. When the differences between the computed sound pressures exceed 1 db, it is advisable to include the data from a third standard in order to identify the cause of the discrepancy.

Receiving Response Measurements. Instruments which have been designed for hydrophone operation are calibrated in a sound field established by the procedure described above. The instrument is oriented acoustically before any test data are recorded, but the device may or may not be tuned according to the specifications of the program.

On the basis of an exploratory observation, the gain of the receiving amplifier is adjusted so that the curve will remain on the chart as the frequency range is covered. If the level range of the instrument exceeds that of the recorder, it may be necessary to change the gain during the course of the run or to repeat a portion of the curve at a different gain setting. Runs at several test distances usually are recorded on the same chart and, if possible, with the same gain.

In the case of sharply resonant devices, supplementary records are made of the level at peak frequency by slow manual variation of the oscillator. Measurements at frequencies on each side are made until the levels are 3 and 10 db below the peak response. These observations permit determining the Q of the instrument.

In general, the response of essentially nondirectional apparatus is taken at several angular positions such as 0, 90, 180, and 270 degrees. Comparison of these runs may show inaccuracies in rigging, particularly at low frequencies where diffraction effects are not likely to occur.

Hydrophone Coupling Measurements. The recorded data are a measure of the signal level at the 135-ohm input to the receiving system in db vs 10^{-16} watt. Since the instrument calibration is usually wanted in terms of open-circuit voltage, or voltage across a specified impedance, it is necessary to determine the relationship between these quantities and the recorder level. This is obtained by injecting a signal from a low impedance in series with the hydrophone circuit, thus simulating the voltage generated under acoustic excitation. The difference in level between the injected signal and the input to the receiving amplifier determines the hydrophone coupling. Typical circuit arrangements for observation of coupling characteristics are shown in circuits A and B on Figure 32.

The hydrophone calibration may be required in terms of the voltage delivered to a specific load resistor. In this case, the hydrophone, bridged by the required resistance, is connected to the coupling amplifier. The conversion of the recorded level to the voltage at the input of the coupling amplifier requires a knowledge of the relation of gain to fre-

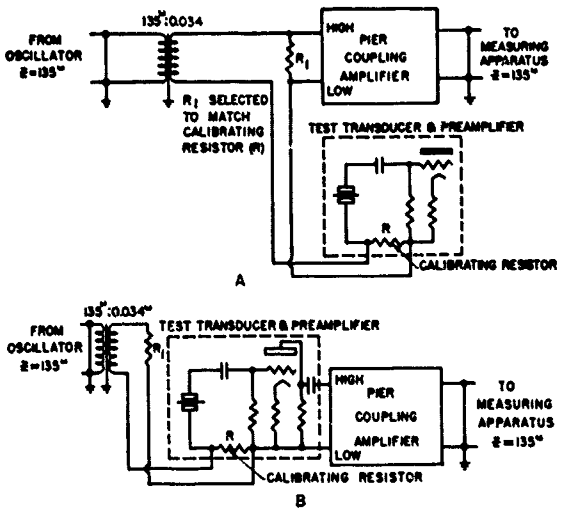


FIGURE 32. Typical circuit arrangements for hydrophone coupling characteristic measurements: (A) observation of input signal, (B) observation of output signal.

quency for this amplifier. This relation may be obtained by using the circuit arrangements shown in Figure 33.

Low-sensitivity, high-impedance hydrophones are usually tested in conjunction with the underwater preamplifier described in Section 6.2.1. This arrangement permits the hydrophone calibration to be referred to the ends of extremely short leads and results in an essentially open-circuit calibration.

An alternative method of calibration, particularly adapted to high-impedance tourmaline gauges, expresses the hydrophone output in terms of the charge generated rather than the open-circuit voltage. This method, described in Chapter 4, requires minor modifications in the underwater preamplifier.

Measurements of Inherent Noise. The inherent noise level of a hydrophone is measured with the instrument in quiet water. When open water conditions

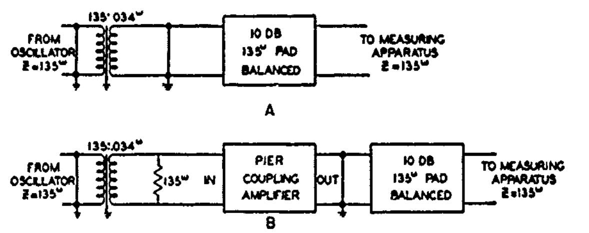


FIGURE 33. Circuit arrangements for determination of gain frequency characteristic of coupling amplifier: (A) observation of input signal, (B) observation of output signal.

are not sufficiently quiet, a bucket with suitable antishock mounting or an acoustically treated tank is used. A highly efficient unit, the noise level of which is greatly affected by changes in the radiation impedance, should not be tested in the bucket because of probable standing waves. In fact, even an acoustically treated tank may allow the formation of standing waves sufficient to prevent exact noise level measurements. Standing waves cause variations in the impedance which the medium offers to the diaphragm. In well-designed radiators, the mechanical impedance of the diaphragm more or less matches the impedance of the medium to which the energy is transferred. The more efficient the device, the less will be the loss between the electric power supplied and the acoustic power radiated and, therefore, the closer will be the coupling between the impedance of the device and the impedance of radiation. Since thermal noise generally is proportional to the resistance, small confined areas which produce standing waves are not conducive to accurate measurements on the more efficient devices.

In order to minimize mechanical vibration, the test units are suspended in low-period antishock mounts and every effort is made to reduce the background noise to a minimum during the observations.

Measurements of the hydrophone noise level and its distribution through the operating frequency range are made on system 2 with each of the acceptance band widths, 10, 300, and 6,000 c, in such a manner that adequate overlap is obtained. To determine whether the noise level of the system is sufficiently high to affect the measurement of the hydrophone noise level, observations are made with a resistor connected in place of the test instrument. The resistance is selected by trial to be small enough so that the thermal noise generated in it is negligible. Progressively smaller values are tried until there is no observable change in the output noise level.

Receiving Directivity Patterns. Directivity patterns of transducers may be obtained rapidly and with good angular accuracy by means of the rotator and recording turntable assemblies described in Section 6.2.1. Exploratory observations are first made to check the angular orientation and to adjust the system gain so that the pattern traced will lie within the boundaries of the recorder paper. Whenever possible, the signal level at zero angle is adjusted to the upper limit of the chart in order to utilize its full 50-db range and to facilitate subsequent chart comparisons

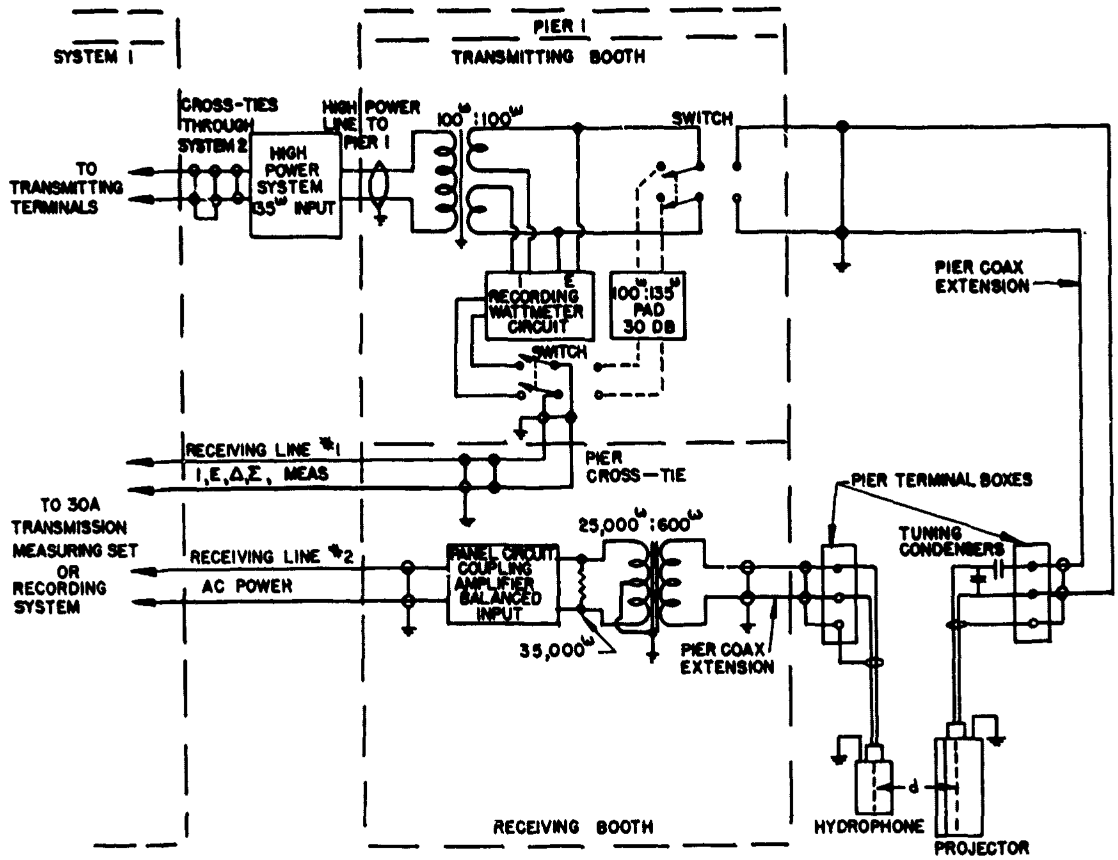


FIGURE 34. Typical circuit arrangement for observations of projector acoustic output versus electric power input.

by superposition. The rate of rotation is selected on the basis of instrument size, driving torque required, and pattern complexity. For example, small devices may be rotated at the maximum rate, provided the rate of signal variations does not exceed the response rate of the recorder.

After the preliminary observations and adjustments, the pattern is recorded with the turntable moving through a complete revolution. Overall system and transducer stability may be checked by noting the recorded trace at the point of overlap.

For all critical test conditions, the pattern should be repeated at a second distance. If the pattern changes radically with distance, this usually indicates too small a test distance (see Chapter 5) or the presence of reflections. In the former, the distance should be increased, while in the latter it should be decreased, the frequency slightly displaced, or other means employed to reduce reflections.

In general, sharply resonant transducers are investigated for pattern characteristics at the frequency of resonance, at frequencies slightly above and below this point, and occasionally at the frequencies of secondary and tertiary resonance.

Design symmetries or asymmetries which control the beam pattern are investigated by making records about several axes of rotation. The positioning of a transducer for an investigation of design symmetry is illustrated in the sample circuit sheet shown in Figure 31.

Split transducers, designed for *bearing deviation indicator* [BDI] operation, may be studied for phase shift and symmetry by means of a special circuit designed by the Harvard Underwater Sound Laboratory.[51] This circuit provides for the halves of the transducer to be in parallel but the connections to one may be reversed so that its output may be in the same phase or opposite to the other. Lag lines giving various phase shifts are readily available and when plugged into the circuit are connected to a three-

position switch which determines that the outputs shall match, or chooses the one that shall be made to lag.

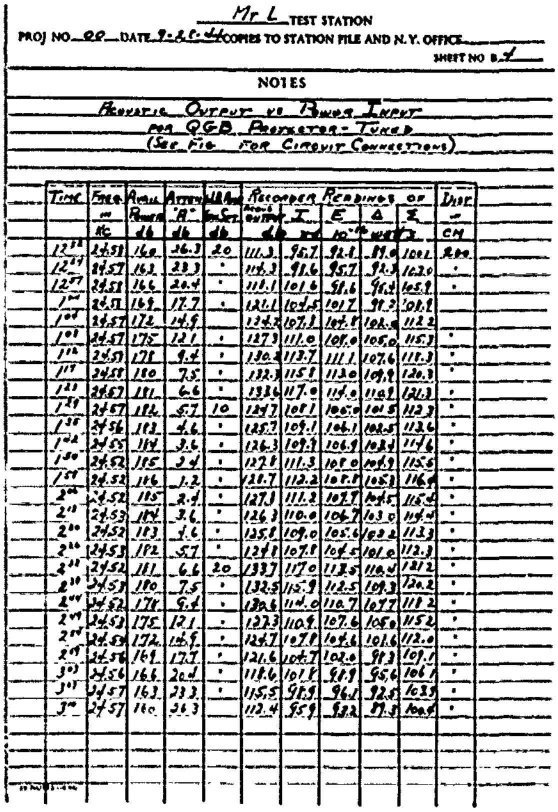
The patterns usually taken for the BDI characterization of a transducer are for halves in phase with no shift, halves in opposite phase with no shift, halves in phase with one shifted to lag, and halves in phase with the other shifted to lag. The gain chosen for the first condition should be maintained for the others. The first two patterns are usually recorded on one chart and the second two on another.

Pattern investigations of hydrophones usually are made with a continuous sinusoidal frequency, but may be made by pulsing within the limits discussed in Chapter 5. It is of interest occasionally to take patterns representing listening conditions with a broad noise band covering approximately the audio range. A 6-kc band centered at 4 kc is most satisfactory.

Transmitting Response Measurements. In obtaining data on transmitters it is not necessary to establish a definite sound field. The calibration is made with standard hydrophones, selected on the basis of frequency coverage and uniformity of response at specified frequencies. Most of the measurements are made with only one standard, but this is checked by at least one other. This is not only to check the standard hydrophone but also to test the projector stability. Most of the preliminary observations are made at low power levels and then extended to maximum values. Projectors are usually calibrated with continuous sinusoidal signals, but tests may be made with pulsed ones, as described above. The impedance from which the projector is driven is selected to agree with the recommended value. A convenient available power level is 160 db vs 10^{-16} watt, but it must never exceed the recommended maximum. (See Figure 29.)

Projectors that require an external tuning circuit for power factor improvement are calibrated both with and without this circuit. Some projectors require a polarizing current, usually supplied through a universal-type junction box. This box provides for the adjustment and metering of the current, and also incorporates adjustable capacitance networks made flexible by a plug-in design.

Preliminary observations include checks on leakage, cross talk, noise, overloading, angular orientation, and required circuit gain. Following these, response data are taken, usually at two distances, and coupling measurements are made for the standard hydrophone used.



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NOTES

Acoustic Output vs Power Input for QGB Projector - Tuned (See Fig for Circuit Connections)

Time	Freq (kc)	Ampl Power (db)	Atten "A" (db)	Hyd Amp Sens (db)	Acoustic output (db)	I	E	Δ	Σ	Dist (cm)
12^52	24.51	160	26.3	20	111.3	95.7	92.1	89.0	100.1	200
12^54	24.57	163	23.3	"	114.3	91.6	95.7	92.3	102.0	"
12^57	24.51	166	20.4	"	118.1	101.6	98.6	95.4	105.9	"
1^00	24.51	169	17.7	"	121.1	104.5	101.7	98.3	108.9	
1^05	24.57	172	14.9		124.2	107.1	104.8	102.4	112.2	
1^08	24.57	175	12.1	"	127.3	111.0	108.0	105.0	115.3	"
1^12	24.51	178	9.4	"	130.2	113.7	111.1	107.6	118.3	"
1^17	24.58	180	7.5	"	132.1	115.8	113.0	109.9	120.3	"
1^21	24.57	181	6.6	"	133.6	117.0	114.0	110.9	121.3	"
1^29	24.57	182	5.7	10	124.7	108.1	106.0	101.5	112.3	"
1^35	24.56	183	4.6	"	125.7	109.1	106.1	102.5	113.6	"
1^42	24.55	184	3.6	"	126.3	109.9	106.9	103.4	114.6	"
1^50	24.52	185	2.4	"	127.8	111.3	108.0	104.9	115.6	"
1^54	24.52	186	1.2	"	128.7	112.2	108.8	105.8	116.4	"
2^00	24.52	185	2.4	"	127.8	111.2	107.9	104.5	115.4	"
2^13	24.53	184	3.6	"	126.3	110.0	106.7	103.0	114.4	"
2^20	24.52	183	4.6	"	125.8	109.0	105.6	102.2	113.3	"
2^26	24.53	182	5.7	"	124.8	107.8	104.5	101.0	112.3	"
2^33	24.52	181	6.6	20	133.7	117.0	113.5	110.4	121.2	"
2^38	24.53	180	7.5	"	132.5	115.9	112.5	109.3	120.2	"
2^44	24.52	178	9.4	"	130.6	114.0	110.7	107.7	118.2	"
2^49	24.53	175	12.1	"	127.3	110.9	107.6	105.0	115.2	"
2^54	24.53	172	14.9	"	124.7	107.8	104.6	101.6	112.0	"
2^59	24.56	169	17.7	"	121.6	104.7	102.0	98.3	109.1	"
3^03	24.56	166	20.4	"	118.6	101.8	98.9	95.6	106.1	"
3^07	24.57	163	23.3	"	115.5	98.9	96.1	92.5	103.5	"
3^10	24.57	160	26.3		112.4	95.9	93.2	89.3	100.4	"

FIGURE 35. Typical data sheet, showing projector output versus electric power input.

Transmitting Directivity Patterns. Directivity patterns about one or more axes of rotation are required in a projector calibration to determine the radiation field. The procedure for taking these with the polar recorder has already been given under *Receiving Directivity Patterns.*

Load Characteristics. Load-run observations to determine the relationships between the various projector characteristics and the impressed power may be made by means of the circuit arrangement shown in Figure 34. These data should include observations of linearity, frequency shift, distortion, and impedance. Additional patterns may be taken to observe the variation of any quantity as a function of power.

Figure 35 is a copy of an original data sheet showing typical load-run observations. The time entries are indicative of the soaking periods allowed for adequate thermal stability to be reached following each change in impressed power. A description of the wattmeters with their circuits and theory is given later in this chapter in Section 6.2.8.

Impedance Data. Impedance data are taken on all

transducers not directly associated with preamplifiers. The devices are usually suspended from the pier, well below the lake surface, while the measurements are made. Occasionally impedance measurements are made with the transducer suspended in the acoustically treated tank. Such data are checked for standing wave effects by repeating a few observations from a different position. The temperature of the water adjacent to the transducers is always recorded and an adequate soaking period is provided to permit complete thermal equilibrium.

Observations on wide-band transducers that have no sharp resonances are taken to cover the frequency range in increments which will permit the construction of accurate resistance and reactance curves. Additional observations are taken on resonant transducers in the resonance regions, so that motional impedance computations may be made. These observations include not only measurements at the frequency of maximum response but also at frequencies above and below this value until the response is less by 0.5, 1, 2, 3, 5, and 10 db.

After considering the bridges available for direct impedance measurements, the usual procedure is to take the series impedance, if its value is not over 10,000 ohms and one terminal can be grounded, and the shunt admittance for larger values and devices that cannot be grounded. Some attention must be given to the choice of the frequency that should be used. A description of the bridges is given in Section 6.2.8.

Whenever possible, measurements are made at the apparatus terminals but when additional cable must be used, measurements are made of the device with cable, and of the cable alone, so that a correction for the latter may be applied. To facilitate making these corrections, all bridge readings are expressed in the same unit, that is, impedance or admittance. When auxiliary apparatus is used, impedance measurements are also made on it to allow the computation of the values for the instrument itself regardless of the circuit used.

The impedance of a transducer may also be obtained from the readings of the wattmeter and though the accuracy is not as good as with the bridge, it affords a continuous indication and permits the detection of all resonances. It has the further advantage that impedance data is obtained at all power levels, instead of at the low levels bridges require, and impedance as a function of power may be observed.

Reciprocity Test Procedure

Several times during the year a series of free field reciprocity calibrations are made on all of the laboratory standard hydrophones. Comprehensive periodic checks are essential, since most of the calibration work is based on an accurate knowledge of the performance of these instruments. A large part of the preparation procedure is identical with that in comparison testing. The instruments are rigged, washed, and oriented in the same manner. The required measurements include response, hydrophone coupling, and projector current, but the number and sequence differ materially. A discussion of the theoretical considerations involved in reciprocity calibrations and of the general procedure used is presented in Chapters 5 and 7. Actual procedures are discussed herewith.

Requisites. A reciprocity calibration requires the use of a reversible transducer which obeys reciprocity. Since two semi-independent calibrations can be obtained with little extra effort by using a pair of such transducers, this procedure is considered. It may be necessary to use several pairs of transducers to cover the frequency range from 15 c to 150 kc. In each test run, one of the given pair operates as a hydrophone, while the other furnishes the sound field. In a reciprocity calibration it is necessary to know the open-circuit voltage of the instrument, although it may be more convenient to measure the voltage across a known impedance and calculate the open-circuit value. The driving and receiving impedances are selected to provide the most uniform frequency response. The equations given in Chapter 5 require a knowledge of the distances between the acoustical centers. The selection of a center is arbitrary but, once selected, must remain the same throughout the test. It is usually chosen to approximate the center of the spherical waves which the transducer produces at large distances and for this reason, runs are taken at several hydrophone-projector separations. From the distance-loss relationships, the effective acoustic center of the transducer can be determined. The runs also assist in evaluating the effect of reflections and standing waves.

Testing Procedure. It is indicated in Chapter 5 that there is no simple *a priori* test that determines whether or not a particular transducer obeys the reciprocity

principle. The most satisfactory substitute is a cross check between two reversible instruments separated by a fixed distance. With one functioning as a hydrophone and the other as a projector, the ratio is obtained of the open-circuit voltage developed by the one to the current supplied the other. The electric connections are then interchanged and the runs repeated, giving the same ratio with the function of each reversed. If the two transducers obey reciprocity, these ratios will be equal at each frequency. It is possible that these ratios may be equal, even though the transducers do not obey reciprocity, but there is little chance of this unless the transducers are identical, in which case they may violate the reciprocity principle to the same degree.

When reciprocity has been established, the transducers are placed at opposite ends of the testing area with no change in their orientation or depth. The hydrophone to be calibrated is then mounted on a movable carriage between the two and tested against each in turn. The procedure outlined in Chapter 5 is then carried through, using each transducer as a projector and as a reversible transducer as described. This procedure yields two semi-independent reciprocity calibrations of the hydrophone. It is usual to test successively all hydrophones of the same type, since this procedure entails a minimum number of changes in rigging and electric connections.

Other Free Field Acoustical Observations

In addition to the usual calibrations, acoustic studies are made which involve somewhat different testing techniques, such as observations on domes, baffles, generators of complex acoustic waves, and complete echo-ranging systems.

Dome Studies. When a dome is submitted for investigation, the projector to be used with it may not be included and a suitable one must be selected. It may be a wide-band device or a sharply resonant one, but it must have low side lobes at the frequencies of interest and have as nearly as possible the same size and directivity as the projector for which the dome was designed. This is very important, since a projector with unsuitable directional characteristics can completely obscure important dome characteristics.

The transducer is usually tested first without the dome by rigging to the inner shaft of the rotator. The measurements ordinarily include frequency response as a hydrophone or as a projector and directivity patterns as a hydrophone. The character of the transducer will largely determine the frequencies at which the dome is tested. If the transducer is sharply resonant, patterns may be taken only at the resonant frequencies.

Following these tests the dome is thoroughly cleaned and rigged to the outer shaft of the rotator with care being taken to insure correct positioning of dome to transducer. The assembly is then debubbled and allowed to reach temperature equilibrium.

The type and character of the test data required for a comprehensive investigation are illustrated in Table 1. Figure 36 shows the various configurations of the acoustic gear. Because of reciprocity, as shown in Chapter 5, the effect of the dome, the baffle, and their surroundings on the response and directivity of the transducer is the same on sending and receiving. For practical reasons, receiving is preferred.

There are considerations in making dome directivity tests which require somewhat different arrangements. To investigate the effects of either a given target or a noise source located at a definite bearing, the nose of the dome is set at the bearing and the transducer alone is rotated as indicated in Figure 36D. The same procedure with the dome reversed, as shown in C, is used to simulate the propeller noise from one's own ship. The effect of the dome on the pickup of water noise and reverberation for any particularly trained position ϕ of the transducer can best be shown by rotating the dome and projector together with the angle ϕ between them fixed during each trial (Figure 36E). This plan calibrates the response of this combination of dome and transducer to noise from any direction.

Accurate positioning of the dome and hydrophone is easily accomplished by means of the rotator and turntable. Either rotator shaft may be locked in position while the other is rotated. It is thus possible to secure the required angular separation between the hydrophone face and the dome nose. By engaging both shafts, the whole assembly may be rotated while the relative angular position of dome and hydrophone remains fixed.

Baffle Studies. The reflective and absorptive properties of baffles may be studied independent of domes. While no direct measure of absorption is made, this characteristic may be estimated from reflection and transmission measurements. The testing arrange-

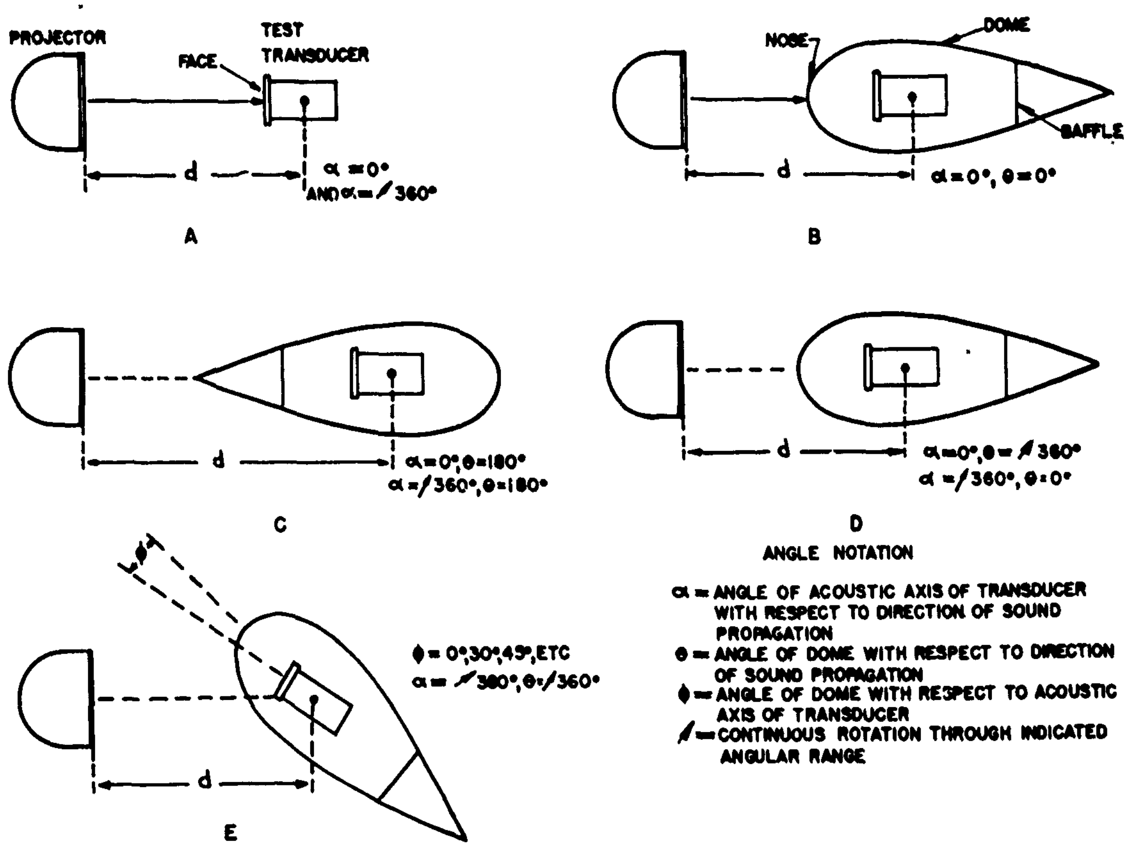

FIGURE 36. Typical testing geometries for dome and baffle measurements: (A) reference runs, (B) transmission through nose of dome, (C) transmission through baffle, (D) dome loss versus angle, (E) specular reflection studies.

ments are shown in the sketches of Figure 37. Comparison of the reference pressure obtained between the hydrophone and projector with and without the baffle gives the insertion loss characteristic of this baffle. A sound pressure is present on the far side of the baffle because of transmission through the baffle and diffraction around it. This is more fully discussed in Chapter 9.

The reflecting and absorbing properties of the baffle may be further studied by modifying the testing setup as shown in Figure 37D. The baffle and transducers are positioned so that the over-all path length of the reflected sound is equal to *d*. With the baffle removed, a screen is placed between the projector and hydrophone as in Figure 37C to minimize the direct transmission. The magnitude of the sound received determines the threshold in the reflection measurements. If the sound pressure measured by the hydrophone, with baffle in place as in Figure 37D, is equal to that measured in the reference run of 37A, the baffle is a perfect reflector. The amount by which the two differ is a measure of the sound transmitted, absorbed, and diffracted by the baffle.

Studies of Acoustic Properties of Various Materials. Occasionally the acoustic properties of a particular material are investigated to determine its suitability for a proposed application. Reflection and transmission tests, similar to those made on baffles, are made on samples of the material. These should be large enough to avoid diffraction in the frequency range under consideration. Before testing, the samples are thoroughly washed, debubbled, and submerged until they are in temperature equilibrium with the water. Often additional tests are made to discover the critical angles at which incident sound will be completely reflected by the material. The sample is rotated in the setup of Figure 37B and the angles observed at which minimum transmission occurs. This information is particularly valuable in the design of dome windows and in the selection of materials for them.

TABLE 1. Test data required for dome investigation.

Purpose of observation	Angular position* α	θ	$\phi = \theta - \alpha$	Arrangement in Fig. 36
Transducer response without dome	0°	...	...	(A)
Transducer pattern without dome	↑360°	...	...	(A)
Transmission response through nose of dome	0°	0°	...	(B)
Transmission response through rear of dome	0°	180°	...	(C)
Transducer pattern with baffle and rear of dome interposed†	↑360°	180°	...	(C)
Transmission pattern through dome vs angular position	0°	↑360°	...	(D)
Transducer patterns through dome	↑360°	↑360°	0° 15° 30° 45° etc., incl. known critical angles	(E)

* Transducer used as a receiver only.

† If the dome is equipped with a removable baffle, tests should be made with (a) dome and baffle, (b) dome alone, and (c) baffle alone, to see how baffle and dome affect noise pickup over a range of angles about the rear of the transducer.

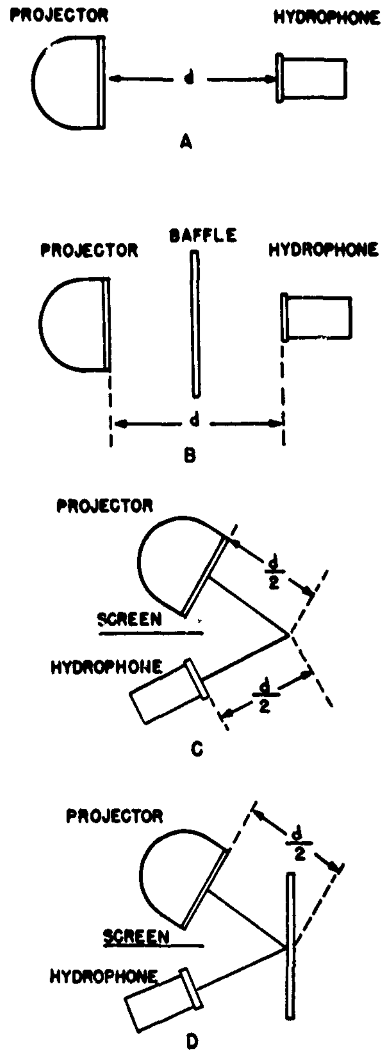

FIGURE 37. Plan view of typical test set-ups for studying baffle characteristics: (A) reference runs, (B) sound transmission through baffle, (C) threshold signal without baffles, (D) sound reflection by baffle.

Studies of Acoustic Wave Signal Generators of Complex Waves. Devices designed to generate acoustic signals of complex wave forms are divided into two major categories, each requiring a special testing technique. In general, the choice of technique is based on such factors as a continuous signal, recurrent signal and its rate, and the crest factor (ratio of peak to rms values).

Obviously, the use of electromechanical equipment for the recording of random events is limited by such factors as the speed and dynamic range of recorder response. Signals that are intermittent, that have low recurrence rates, and those with crest factors greater than 2.5, are usually studied by means of a cathode-ray oscilloscope and high-speed oscillograms. Signals that are continuous or of high recurrence rate, with crest factors not exceeding 2.5, may be studied with the apparatus of system 2. The procedure for investigating such signals with system 2 is stated herewith and may be used for those of periodic or aperiodic nature.

The devices are rigged and positioned with the usual procedure for testing projectors. Provision is made for the observation and control of the driving power. A standard hydrophone having a substantially uniform frequency response is selected for the acoustic pressure measurement. In the selection, the maximum instantaneous pressure must be considered in order to avoid overloading of the preamplifier.

Observation of the crest factor should be made first with the arrangement shown in Figure 38, where the rms of the signal is obtained on the 30A set and the peak amplitude on the cathode-ray oscilloscope. The complex wave signal is then replaced by a sinusoidal one from an oscillator set at a level which gives the

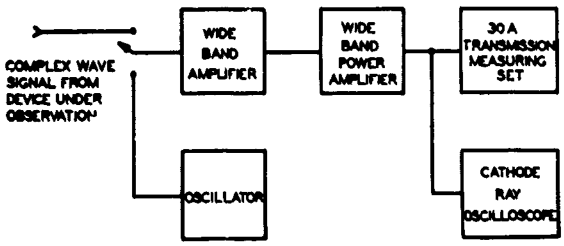

FIGURE 38. Simplified circuit arrangement for determination of peak factors.

same deflection on the oscilloscope as the test signal. The difference between the 30A set readings on the test and oscillator signals gives the difference in db between the crest factor of the complex wave and that of the sine wave. Since values are being determined in volts and a sine wave has a crest factor of 1.41 (= 3 db), this amount has to be added to the observed difference in db before reverting to the ratio that expresses the crest factor of the complex wave.

The investigation includes observations of the total (broad-band) energy and of the energy distribution with respect to frequency from 100 c to 150 kc with the receiving amplifier output connected directly to the broad-band recorder. The examination of energy distribution with respect to frequency over the test signal spectrum can be made with the normal facilities of system 2, which has three acceptance bands in the detector circuit, 10, 300, and 6,000 c. As these bands become a continuously smaller percentage of the frequency as it increases, the 10-cycle band usually is carried only to 20 c and the 6-kc band is not used below 4 kc. When the recurrence rate of the signal is too low, the recorder will follow the individual cycles which involve the difficulty of evaluating wide and irregular traces. Suitable resistors are inserted in the pen-drive motor circuit to reduce the response rate and thereby minimize the recorder excursions.

The energy in band widths other than those provided by the detector circuit may be obtained by the use of the circuit arrangement shown in Figure 39. The plan of this circuit is to transpose the signal frequencies by heterodyning them so that the desired signal band may be obtained with available filters. The method is illustrated in Table 2, which gives the value of the signal frequency at various stages, with the circuit adjusted to pass only a band of frequencies 1 kc wide centered at 10 kc.

Band widths commonly used in such investigations include 5 ± 0.25 kc, 10 ± 0.5 kc, 20 ± 1 kc, 30 ± 1.5 kc, and 40 ± 2 kc. It is obvious, however, that the system may be adjusted for any band width and mid-band frequency requirement within the limits indicated on Figure 39.

A determination of the rate of signal recurrence is usually made by inspection of the broad-band recorder traces. For high values, the speed of paper drive on the recorder should be at a maximum.

The investigation of the operational stability or life characteristics of expendable devices is made by

TABLE 2. Value of signal frequency in kilocycles per second at various stages when circuit is adjusted to pass all frequencies in the band 10 ± 0.5 kc.

The dial setting of the heterodyne oscillator is 12.5 kc to obtain 637.5 kc. This is the sum of the lowest signal frequency to be passed and the half-band width of the filter in the detector circuit added to a fixed frequency.

Frequency of oscillator No. 3 is set at the sum of upper cutoff frequency of the detector filter and the cutoff frequency of the low-pass filter minus the desired band width.

xxx indicates the filter that cuts off the frequencies outside the desired band.

Freq. of signal	Var. freq. osc. No. 2	Mod. No. 1 output	Mod. No. 2 output	B.P. filter output (Detector circuit 91–100 kc)	Osc. No. 3	Mod. No. 3 output	15 kc L.P. filter output
		A + B	747-C			F − E	
9.0	637.5	646.5	100.5	xxx			
9.5	"	647.0	100.0	100.0	114.0	14.0	14.0
10.0	"	647.5	99.5	99.5	"	14.5	15.5
10.5	"	648.0	99.0	99.0	"	15.0	15.0
11.0	"	648.5	98.5	98.5	"	15.5	xxx

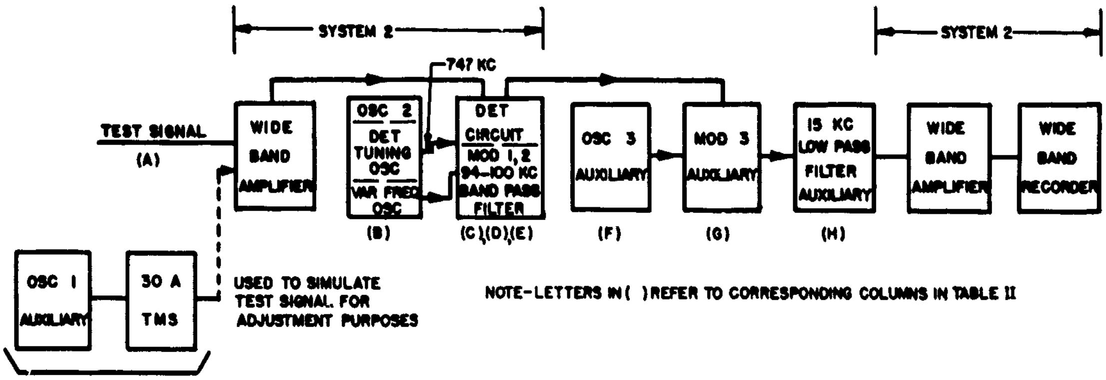

FIGURE 39. Simplified circuit arrangement using System 2 with auxiliary apparatus for obtaining a band-pass filter adjustable in width up to 6 kc and with a mid-band frequency variable between 3 and 150 kc.

permitting the recorder to run for an adequate period with the circuit arranged for broad-band observations. The synchronous motor of the paper drive measures the time of these observations and the paper speed should be at a minimum.

The circuit arrangement in Figure 40 permits observations on the effectiveness of complex acoustic signals in aural masking. A variety of characteristic sounds on phonograph records is available with which to study masking effects at sonic or supersonic frequencies.

Operational Studies of Complete Echo-Ranging Systems. With the apparatus connected into a complete system for echo ranging, actual trials are made to test the ability for locating small objects in shallow water at distances under 350 meters. A common method is to suspend a small target from a rowboat which travels slowly over the range while the attempt is made to locate the target and maintain contact with it. Common targets are 2- and 3-foot hollow spheres and a 4-foot length of 7-inch heavy walled pipe. One of these is suspended from the stern of the boat at the same depth as that of the transducer. Directions for the course of the boat and other communications between operators are carried on by radio telephone.

The raft has a working space running its full length through the center. The apparatus rests on carriages moving on steel rails the same as on the piers while an overhead rail and hoist facilitates positioning on the carriages. The monorail on pier 1 offers the easiest transfer of equipment to the raft, which must be kept level by proper weight distribution. With the gear in place, the raft is located at one end of the range and secured to the shore by 1-inch cables with wide angular spacing. Connections are made to the power and signal lines, which include a

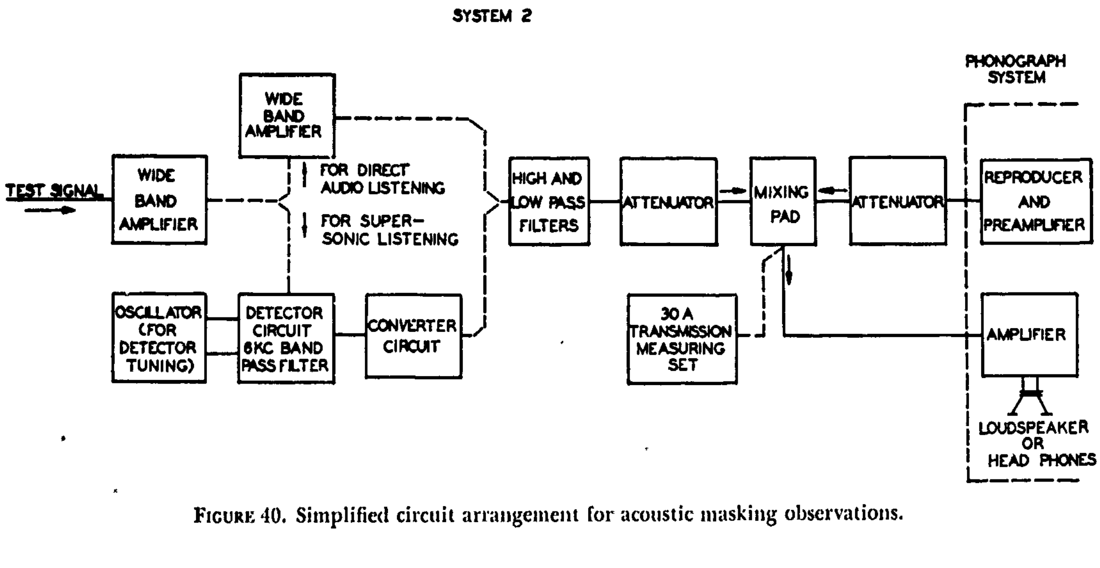

FIGURE 40. Simplified circuit arrangement for acoustic masking observations.

telephone to the laboratory. The raft carries permanently a 6-kva, 60-cycle regulator that will maintain any voltage from 105 to 125. Canvas drops are supplied to protect the operators in bad weather.

Temperature gradients in the lake are checked by bathythermograph records taken several times throughout the test period. Since factors such as gas-bubble accumulations on the bottom may affect the acoustic conditions, it is advisable to make simultaneous observations on a reference system maintained at the laboratory for this purpose.

6.2.3 High-Frequency System

GENERAL DESCRIPTION

The high-frequency system at the Mountain Lakes laboratory covers the range from 100 kc to 2.2 mc. While the electronic system is capable of calibrating up to 3 5 mc, no standard transducers are available for those frequencies.

The system comprises the following items:

1. An ele tric system capable of producing, measuring, detecting, and recording signals in the frequency range 50 to 3,500 kc.

2. An indoor calibratio tank with the necessary mechanical equipment for positioning and aligning the units under test. Included here also are the various acoustical devices for the reduction of reverberation.

3. Two sets of mechanically interchangeable transducers having overlapping frequency responses, with one set covering the range 100 to 800 kc and the other 300 to 2,200 kc.

4. Mechanical and electrical components for measurements in the outdoor test areas. These subjects will be treated in detail in the following paragraphs.

ELECTRIC SYSTEM

The electric system consists of a heterodyne oscillator, power amplifier, and coupling network for driving a projector, and of a detector and recording circuit coupled through a preamplifier for measuring the output of a hydrophone. This system will make continuous ink recordings of the combined response of a pair of instruments throughout the frequency range 50 to 3,500 kc. A block diagram of this system is shown in Figure 41. The frequencies and signal transmission direction are also shown on the diagram.

Oscillator. The heterodyne oscillator consists of one oscillator fixed at 15 mc and the other variable from 11.5 to 15 mc. Each feeds through its own buffer to the same modulator, which is followed by a filter designed to pass only the difference frequencies of the oscillators. An amplifier stage follows the filter and terminates in a transformer designed to supply a 72-ohm impedance. A standard attenuator of this value is inserted between the transformer and the output jack of the oscillator.

As the block diagram indicates, a small portion of the output is rectified, converted, amplified, and fed into the buffer stage for the fixed oscillator. This constitutes an *automatic volume control* [AVC] which will hold the output within 0.15 db over the entire frequency range, while without it, the variations may be 1.5 db. The maximum output of the oscillator is 222 milliwatts corresponding to 4 volts across 72 ohms and the harmonic level is 45 db below that of the fundamental frequency.

The mechanical construction is very similar to that of the other systems. The variable-frequency oscillator can be driven either by hand or by a synchronous motor which allows the entire range to be covered in 1.5, 4.5, or 13.5 minutes. The calibrated scale is a 30-foot strip of 35-millimeter film. Values may be determined between the lines of this scale by interpolation with a vernier dial.

The oscillator frequency is adjusted to the scale calibration at 76 kc by means of a high-Q tuned circuit and at 2 mc by means of a quartz crystal. These adjustments are made by a trimmer condenser and a small adjustable inductance in the circuit of the variable oscillator. A frequency check is made several times each day to correct for any drift. This effect, however, becomes negligible after 72 hours of continuous operation and accordingly, the power is not turned off, unless it is to be for a period of several days.

Power Amplifier and Power Level Measurements. The power amplifier is the wide-band type, covering 50 to 3,500 kc with a gain of 35 db flat to 0.5 db. The input and output impedances are both 72 ohms and the maximum power available is 25 watts (174 db vs 10^{-16} watt). It should be noted that the output of this amplifier can be either balanced or unbalanced with respect to ground.

As indicated on the block diagram, a power level measuring set is used to measure the available power at the output of the oscillator or power amplifier. This instrument is a high-frequency equivalent of the Western Electric 30A transmission measuring set.

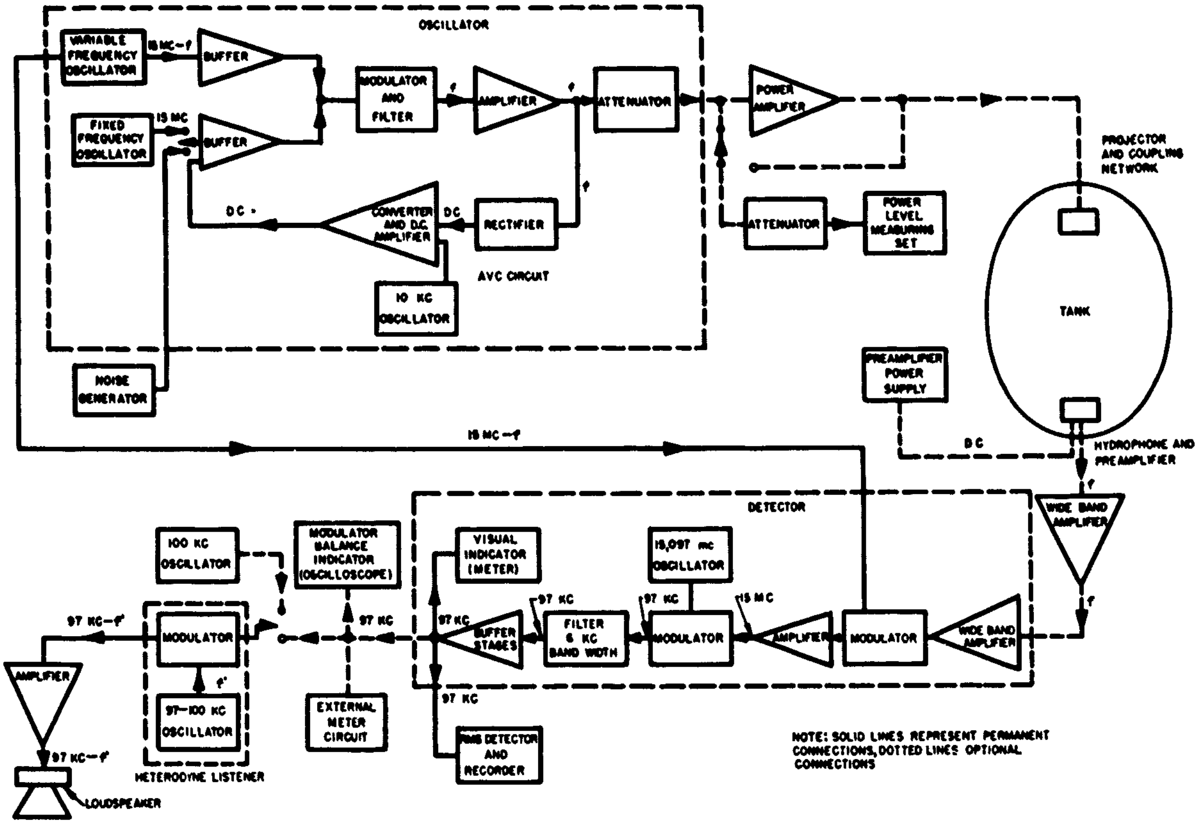

FIGURE 41. Block diagram of high-frequency system.

It consists essentially of a high-frequency thermocouple calibrated on direct current and matched to 72 ohms. When properly used, this instrument will measure the power dissipated in a 72-ohm load.

Projector Coupling Network. The purpose of the projector coupling network is to match the impedance of a projector to that of the driver and the associated transmission line. Arrangements are also provided for measuring the current to the projector.

The most common network is a transformer that is designed for standard instruments over this range of frequencies. The majority of the projectors encountered have the same general characteristics as the standards and so operate satisfactorily with this transformer. If a closer match is required, various resistances may be added to bring the impedance to the desired value.

The transformer for high-frequency standards has a nominal impedance ratio of 72:1,000 ohms and is designed especially for a capacitive (crystal) load. Other ratios used are 72:20, 72:72, 72:250, and 72:2,000.

Hydrophone Coupling Circuit. For high-impedance hydrophones the usual coupling circuit is a high-impedance input amplifier. Since it is necessary to match the coupling circuit to a low (72-ohm) impedance transmission line, it is convenient to look upon these coupling circuits as impedance transformers. One of the best electronic circuits for this purpose (an electron tube is necessary because of the high input impedance requirements) is a cathode-follower type circuit. These circuits used in connection with underwater acoustic devices are known as preamplifiers. The single-stage preamplifiers used in the high-frequency system have an input impedance of about 25 megohms in parallel with about 5 $\mu\mu$f. The output impedance is 72 ohms balanced or unbalanced and the gain is -20 db flat to within 0.25 db over the entire range. One preamplifier is designed particularly for the high-frequency standards, while the others are portable for use in current measurements and with other hydrophones.

It should be noted that the abnormally high values of grid resistors are not necessary as at the lower fre-

quencies because the input capacity is the controlling impedance.

A calibrating resistor has been included in these preamplifiers to obtain the coupling loss of the circuit, which is required in order to evaluate the open-circuit voltage of the hydrophone.

Wide-Band Amplifier. The wide-band amplifier shown on the diagram has a gain of 40 db and is flat within 0.25 db from 50 kc to 3.2 mc. At 3.5 mc the response is down 3 db. Both the input and output impedances are 72 ohms.

The purpose of this amplifier is to increase the signals that are too small to record, even with the full gain of the detector.

Since the amplifier is unbalanced, it is associated with a combination of 72:72-ohm coils which allows changing the condition to ground from unbalanced to balanced and vice versa. By means of terminations on the coaxial jack-strips, the coils and the amplifier may be connected to any portion of the circuit, though they are normally used as shown in the diagram.

Detector. The action of the detector is best explained by tracing through a signal from the input. The signal frequency is first amplified and then impressed upon a modulator which receives another signal from the variable-frequency oscillator, the value of which is 15 mc $-f$.

One of the modulation products (15 mc $-f+f=$ 15 mc) is selected, filtered, amplified, and led to a second modulator. The second signal to this modulator is from a local oscillator with a frequency of 15.097 mc, which gives 97 kc as one of the modulation products of this stage. This signal is carried through a band-pass filter centered at 97 kc and 6 kc wide to succeeding stages of amplification.

The reason for bringing the 15 mc $-f$ signal to the detector is that it ties the detector so completely to the oscillator that it will detect no signal more than 3 kc on either side of the one to which the oscillator is set. The principal advantage of this plan is that since most of the amplification takes place in a channel 6 kc wide, a much better signal-to-noise ratio is obtained. One other advantage is relative ease of recording at a single frequency (97 kc) as compared with wide-band recording. The final stages consist of amplifiers and buffers for the 97-kc signal. A meter with a logarithmic scale may be connected beyond these stages to indicate the signal level. This is particularly useful when aligning and positioning the instruments in the tank.

The purpose of the buffer stages is to isolate various circuits from each other. One buffer output goes directly to the rms detector and recorder. The others are used for monitoring and for making frequency adjustments.

To correct for drift in the 15.097-mc oscillator, provision has been made for checking and maintaining the 97-kc carrier in the center of the 6-kc pass band. A visual indicator of frequency drift such as that used in the other systems is not practical because of the relatively larger drifts in this system and because the eye is unable to perceive flickers above 30 per second. As mechanical shock alone may change the frequency as much as 100 c, tone discrimination by the ear is the method used. The 97-kc signal is led to a heterodyne listener consisting of a 94- to 100-kc oscillator, a modulator stage, and a loudspeaker. If the listener is set at 97 kc, no tone will be heard from the speaker when the carrier is 97 kc, but any drift from this will be observed as a beat-frequency tone. A separate quartz-crystal oscillator of 100 kc is available for calibration of the heterodyne listener.

As is the case with all balanced modulator circuits, spurious signals will arise if there is lack of proper balance. As the first modulator stage in the detector is of this design, some provision must be made for indicating the point of balance. In this particular circuit, the modulator unbalance results in an amplitude modulation of the 97-kc carrier, which is greatest when the signal in the detector input is 97 kc. Using a cathode-ray oscilloscope to observe the 97-kc carrier envelope, the balance controls are adjusted for minimum amplitude modulation of the carrier. Audible monitoring of the carrier can be used in conjunction with the oscilloscope and provides an extremely sensitive indication of the balance point. The tone at this point will be noticed to lose its "mushiness."

The external meter circuit shown in the block diagram is somewhat similar to the meter circuit in the detector but has the advantage of being portable, which allows its use for aligning the acoustic instruments in the pier test areas away from the electric system.

The detector input is 72 ohms unbalanced and the gain of the detector plus recorder is such that 75 db vs 10^{-16} watt into 72 ohms is required to produce a

full-scale deflection on the recorder. The noise level under these conditions is off the lower end of the recorder scale, which means that it is below 30 db vs 10^{-16} watt into 72 ohms.

Recorder. The recorder circuit used in this system is practically identical with those of the lower frequency systems and operates only at 97 kc.

Frequency-calibrated paper is available but only for one relative speed of oscillator to recorder. However, if it is necessary to make records at other speeds, calibrated transparent scales may be used.

Indexing circuits for marking uncalibrated paper at predetermined points on the oscillator scale are available. Indexing, however, is done only when a special paper is being used, or when directivity patterns are being taken.

Noise Generator. As shown in the block diagram, the noise generator may be substituted for the fixed oscillator at the entrance to the first buffer stage in the high-frequency system. The noise signal is a 6.6-kc band centered at 15 mc and, as this is heterodyned with the variable-frequency oscillator, the resulting output is the same width centered at the frequency *f*.

The random noise signal is first generated by a gas discharge tube (RCA 150-30), amplified and fed through a 1.1-kc band-pass filter centered at 455 kc. It is then used to modulate a 2.095-mc signal from a crystal oscillator, and the products in the band centered at 2.5 mc are selected, doubled, and then tripled in frequency. This gives as an output a band of noise 6.6 kc wide, centered at 15 mc. The maximum signal level is approximately 0.5 rms volts across 72 ohms.

The addition of a narrow band-pass filter and a local 455-kc oscillator in the noise generator makes it a very useful tool for accurately aligning the fixed-frequency oscillator at 15 mc. This is done by first adjusting the variable oscillator to one of the film scale calibration points with the noise generator and filter circuit substituted for the fixed oscillator. The fixed oscillator is then replaced in the circuit and its trimmer capacitors adjusted until the same calibration point is attained.

Power Requirements and Power Supplies. The entire electric system is powered from the regulated 115-volt, 60-cycle source available in the laboratory. The filament supplies to all the tubes are constant voltage transformers which give additional regulation to the electronic circuits. This type of transformer may be used, since the harmonics arising from this regulation do not interfere with the measurements. This becomes obvious from the fact that the lowest frequency detectable with this system is 50 kc; this simplifies considerably the various power and distribution requirements.

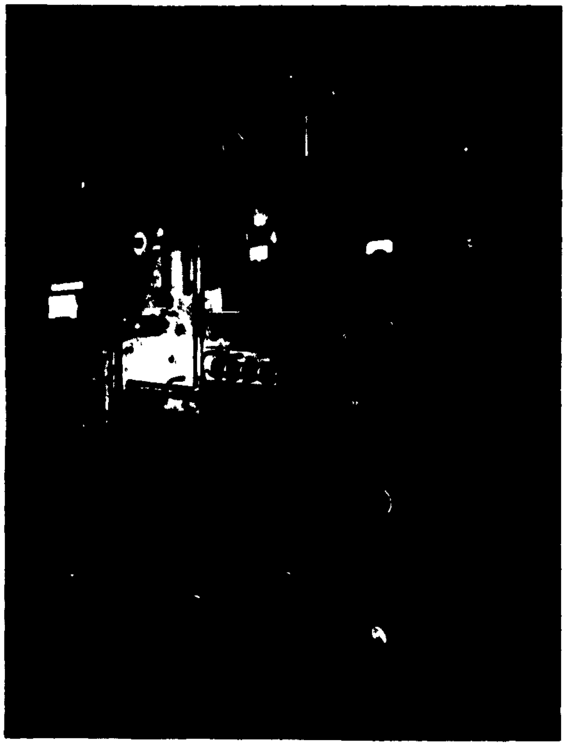

FIGURE 42. Electrical equipment of high-frequency system.

The plate supplies are three units of regulated d-c power which can supply up to 450 milliamperes at 300 volts and are identical with the units used on the intermediate-frequency systems.

For the low-level signal circuits (hydrophone preamplifiers and wide-band amplifier) a special supply was constructed with higher regulation than the above. This unit furnishes 150 milliamperes at 140 volts with a stabilization ratio of approximately 1:10,000 and an internal resistance of about 1 ohm. A similar power supply is available for use with the outdoor test equipment and is built into the same portable case with the external meter circuit.

Transmission Line and Jack Fields. The photograph of the electric system (Figure 42) shows the transmitting jack field below the oscillator and the receiving jack field below the detector. Transmission

lines connect each of these fields with the corresponding junction box at each end of the tank. There are also crossties between the boxes as well as between the jack fields.

With the exception of the control lines for indexing, reporting, and directing, all lines and crossties are standard rubber-covered coaxial cable and terminations are all coaxial jacks (Western Electric Type 464A). This type of line and terminal is also used on the d-c power leads to the hydrophone preamplifiers, since in some instances pickup in the power leads will be impressed on the signal leads by stray coupling capacities in the preamplifiers. Connections to the jack fields and to the instruments are made with patch cords terminating in standard coaxial plugs (Western Electric Types 337A and D122403). The control lines are all standard twinex cable terminating in standard telephone jacks (Western Electric Type 218A). The use of such standard jack fields and patch cords greatly enhances the flexibility of the system.

Lines from other systems also terminate in the jack fields. This allows interchange of equipment between systems for special testing. Another feature of the arrangement is that the lines to other systems can be extended to the pier installations by means of their jack fields, thus making measurements in the outdoor test convenient.

The characteristic impedance of the lines is about 72 ohms and the line loss is negligible in most cases. For example, the loss on a complete loop from the high-frequency room out to the end of the pier and back again (about 425 feet) was about 1 db at 2.2 mc and only 2 db at 3.5 mc. However, it must be emphasized that, unless the lines are properly terminated, standing waves will occur and lead to erroneous results.

Ground Loop and Cross Talk Problems. Since ground loop effects and cross talk depend on the components of particular apparatus and their arrangement in the circuit, it is almost impossible to specify conditions which will apply to all circuits. This is particularly true at the high frequencies and the low signal levels encountered in this system. However, some initial precautions are mentioned here.

The first is the use of good shielding which must be extensively employed to obtain satisfactory results. In all the electronic circuits heavy copper shield cans must be used to isolate individual stages in each amplifier, oscillator, etc. It has even been found necessary to use copper shield cans around the metal tubes in order to decrease radiation.

The same precautions have to be used on all external wiring. In most cases, the coaxial cable used for transmission lines has two shields, one wound on top of the other, for more adequate results and all connections are made by coaxial jacks and plugs. It is important to remember that it is just as necessary to shield the high-level lines as the low-level ones. It is even necessary to shield the power leads, particularly those to the low-level circuits.

Adequate filtering (decoupling) must be used in each individual stage for all electronic equipment and extended, in most cases, even to filtering the filament supplies. The latter is particularly true in the case of cathode-follower circuits. In addition, extreme care must be exercised in the choice of ground conditions in each individual stage. All of these precautions are necessary because of lead inductance and stray capacities. In fact, at these frequencies some commercial capacitors will appear inductive and some commercial inductances, capacitative. Resistors must be especially designed to operate at these frequencies.

Even with all the above precautions, trouble due to ground loops may still arise. This problem is overcome by a variety of precautions. The first and most important is to determine a good ground and connect all other grounds to it. In this case, the tank is selected and the heavy copper straps in the bays of electronic equipment are connected to it by No. 2 copper wire. The tank is connected to the fundamental ground at Pier 2 by No. 0 copper wire. Once the grounds are established, it is necessary to connect all shielding to them in such a manner as to minimize ground loops.

Since the ground loop conditions change as the experimental setups change, it is necessary to construct the system with the greatest flexibility in grounding. This is done by isolating from ground the shields of transmission lines and similar equipment and carrying the connections from the shields through the patch cords to the particular piece of equipment terminating the line. The shields could be connected to ground at this point or isolated by means of a doubly shielded transformer. In general, it was found best to ground the line at one end only, and leave the other end floating. However, all these matters are subject to experimental conditions.

The subject of ground loops and cross talk would

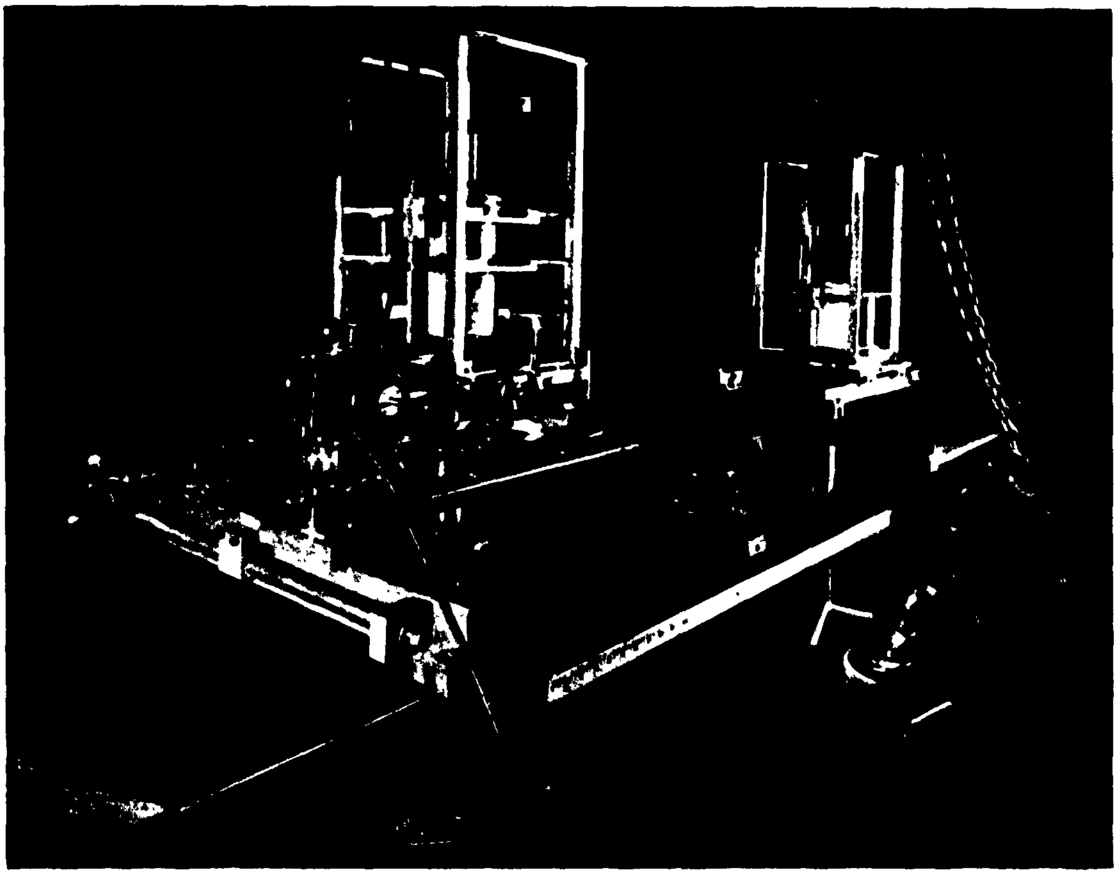

FIGURE 43. View of high-frequency calibration tank, showing mechanical equipment for holding and positioning the instruments.

not be complete without emphasis on internally doubly shielded transformers. These make it possible to transmit or to receive, at will, on balanced or on unbalanced lines. Under most circumstances, balanced lines are much more effective in reducing cross talk and the use of the internal shields on the transformers results in the lumping of all stray capacities between the shields, reducing cross talk still further. These transformers also allow a better treatment of the ground loop problem and are used for coupling between all circuits and lines.

ACOUSTICAL SYSTEM

The acoustical system, in general, consists of an indoor calibration tank, mechanical equipment for holding and positioning the instruments, absorbers for reverberation control, transducers, and outdoor test equipment.

Calibrations may be made in the tank from 80 to 2,200 kc. The lower limit is determined by the reverberation, while the upper limit is imposed by the response of the standard transducers.

Calibration Tank of Positioning Equipment. The calibration tank is made of ⅜-inch steel and has an elliptical cross section with approximate dimensions of 7 feet for the major axis and 4 feet for the minor. The depth of the tank is 4 feet.

The tank has a capacity of 650 gallons and is equipped with a drain and a water inlet at the bottom and an overflow pipe at the top. Water is pumped directly from the lake, and as a result the problem of fungus and slime assumes major proportions. Water from a community system, as a rule, will contain the same organisms, but in much smaller numbers. So many different materials are used in the tank that care must be exercised in the choice of a fungicide. It must be noncorrosive, nonpoisonous, odorless, and only slightly electrolytic. Furthermore, it must have no effect on rubber. Experience showed that a 2 to 5 per cent solution of sodium dichromate was excellent

except for its staining and slightly poisonous nature. However, a commercial product, "Nalco 21M," manufactured by The National Aluminate Corporation, was finally obtained and used quite successfully. This substance comes in small briquettes which are placed in a holder in the inlet water line and requires no attention except replenishing. Its only disadvantage is that it makes the water slightly milky, as do most products of this nature. Its poisonous qualities are negligible as long as the concentration is kept at 3 to 5 parts per million.

The positioning equipment of the transducer (Figure 43) consists of two heavy carriages which can be moved the length of the tank on two steel rails, mounted lengthwise on top. Each carriage provides for positioning the transducer by one screw parallel to the long dimension of the tank and a second at right angles. The vertical adjustment is made by four screws driven at the same rate by a sprocket chain. Rotation may be made about a vertical axis for a full circle.

In addition to these degrees of freedom, one carriage is provided with two more adjustments of the transducer suspension. One permits the vertical angle of the transducer to be changed and the other allows it to be displaced with respect to the axis of rotation. These arrangements are necessary to permit adjustment of the direction of the acoustic axis of the transducer in the vertical plane lengthwise of the tank and to permit rotation of the transducer about an axis through its acoustic center. This same carriage has motor-driven rotation about the vertical axis to facilitate the taking of directivity patterns.

The transducer holders are designed to include the cylindrical case of the preamplifier. Adapters are provided for suspending the nonstandard transducers. The positioning equipment is very rugged in construction in order to reduce vibration and other extraneous motion to a minimum. This is necessary because of the small wave lengths and extremely sharp directivity patterns involved. In addition to the two carriages on the guide rails, platforms are available for suspending other equipment for more complex measurements.

For tests in the outdoor areas, two extra T rails are available that can be suspended from the guide rails. When these rails are fastened in position, the instrument platforms can be mounted on them in the same manner as on the top of the tank. Simpler rigging, consisting of a plate with several cylinders attached,

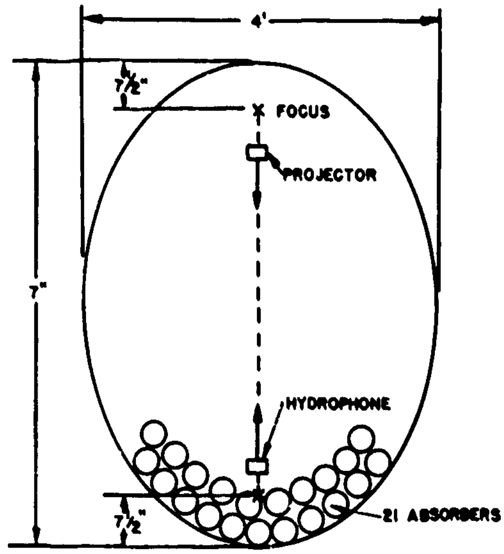

FIGURE 44. Schematic arrangement of absorbers and transducers in high-frequency tank.

is available for special tests. The cylinders fit the standard transducers and the plate is of a size to fit across the guides in the test area.

Reverberation Control. There are a number of factors which influence the reverberation in a tank. Among these are the size and nature of the walls and the directivity pattern (or beam width) of the projector. It is fairly obvious that a narrow beam is much easier to control than is a broad beam that spreads out and strikes the walls of the tank close to the projector.

Since at these high frequencies the beam widths are relatively narrow, it was decided to place absorbing units around and behind the hydrophone only, in such a manner that the portion of the sound beam that passes the instrument will strike the absorbers and be reduced to a negligible intensity. The particular arrangement used is a cluster of 21 cylindrical absorbers grouped as shown in Figure 44. The projector is beamed at the hydrophone from the opposite end of the tank. The tank was made elliptical with the thought that with the projector at one focal point, any stray radiation would strike the walls and pass through the other focal point. If the hydrophone were then placed about 4 inches in front of the focus, the stray radiation would have to pass through the absorbers before striking it. However, it was found in practice that this action contributed little to the reduction of reverberation and that the projector

could be placed anywhere in the tank as long as it was beamed at the hydrophone and absorbers.

Each absorber unit[57] is a hollow cylinder of acoustic rubber 4 inches in diameter and 46.4 inches long, packed with 29 ounces of No. 00 mesh steel wool and filled with deaerated castor oil.

The absorber units are sufficiently rigid to stand unsupported in water. With the particular stacking arrangements used, the sound must travel through the equivalent of four such units before reradiating into the tank. The characteristics of one absorber are shown in Figure 45. The insertion loss for frequencies above 1 mc was beyond the sensitivity of the measuring system and transducers.

Two types of standard transducers are used with this system. One set, with the active face 3 cm in diameter, has an exceptionally narrow beam, and as a result will go down to 80 kc before reverberation affects the results. This type of unit is used up to 800 kc. The diameter of the second type is 1 cm and it is satisfactorily used as far as 2,200 kc. Its directivity is such that reverberation interferes below 300 kc.

One method of minimizing the effects of reverberation is pulsing, which is used with success on the intermediate-frequency systems but has not been tried with this system. The only reason was lack of time. The required modification is not difficult and the benefits to be derived should be as great as in the other systems. Another method that was tried utilizes acoustic lenses. (See reference 57.) The idea behind the use of such lenses was that, if the beam from a small projector could be focused by the lens on the hydrophone, the ratio of signal-to-reverberation intensity should be raised considerably—high enough in most cases to give an accurate evaluation of the sound field.

A lens 10 centimeters in diameter was constructed of polystyrene for operation at 150 kc. A projector was set at 25 cm from the lens center and a hydrophone at the conjugate focus 125 cm on the opposite side. Corrections were applied for spherical aberration and thick-lens effects, and the coincidence of center of curvature and focus was avoided to prevent standing waves. The theory of geometrical optics can be used in designing sonic lenses and if due care is taken the actual lenses will perform according to the theory. For the lens described the increase in signal strength at the focus was calculated to be 11 db for the 1-cm projector and 8 db for the 3-cm projector. These values were obtained experimentally. It should be

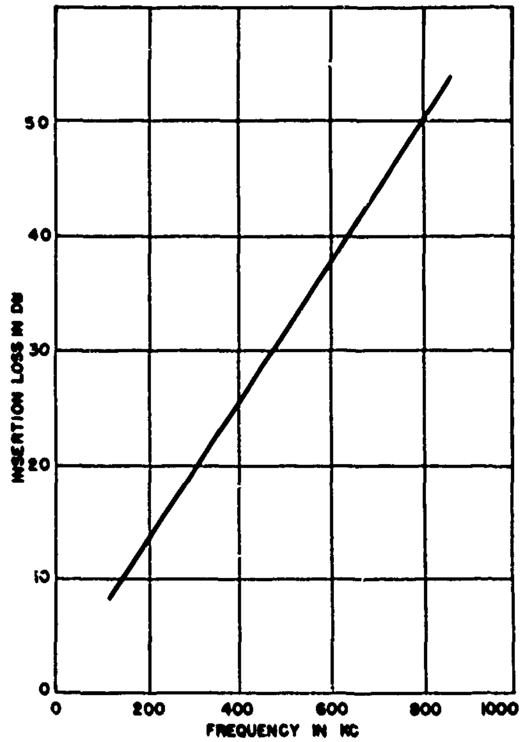

FIGURE 45. Insertion loss of one sound-absorbing unit.

mentioned that lenses can be used in making reciprocity calibrations, if a properly modified parameter is used.

One objection to the use of lenses is that the sound velocity in them changes considerably with frequency. This is to be expected from the analogous optical dispersion, but it adds to testing the difficulty that the instruments which are in focus at one frequency are not at another. To eliminate dispersion, various shapes of reflectors may be used. These behave as expected, but the problem of preparing and maintaining surfaces sufficiently smooth for the high frequencies is too difficult. Another objection to lenses is that the reflections are excessive in some cases. In addition, the lenses are inconvenient to mount and modified parameters must be used in the calculations. All in all, the use of more directive beams and sound absorbers is found to be the most effective.

Standing Waves. Another problem in all acoustical measurements is the presence of standing waves. Even with no reflections from the boundaries of the medium, standing waves may still occur between projector and hydrophone, or simultaneously between each instrument and a third object in the sound field. In

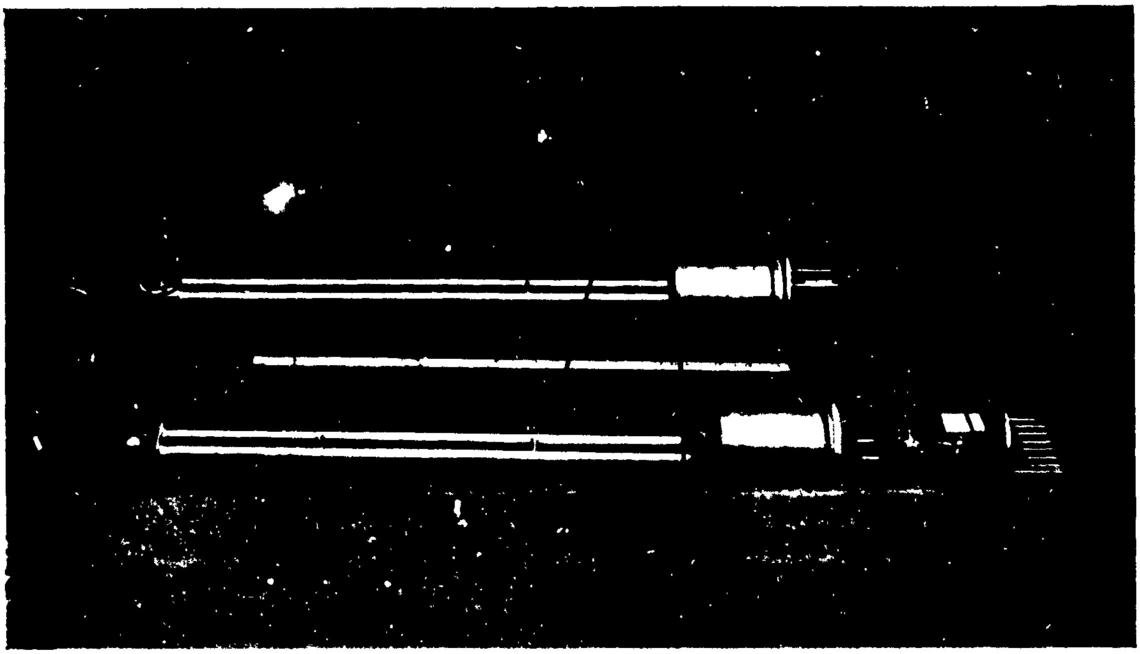

FIGURE 46. High-frequency transducers.

one measurement on lenses, standing waves were generated between the projector and the first face of the lens and between the lens' faces.

It can be shown that, if a condition for interfacial standing waves exists and a frequency sweep is made with a sinusoidal source of sound, the response of the hydrophone as a function of frequency will be composed of a series of alternate maxima and minima. The frequency difference, Δf, between maxima and minima may be shown to be $\Delta f = c/2d$, where c is the velocity of sound and d is the distance between the reflecting surfaces. It follows that, if the sound source is composed of a band of frequencies greater than Δf, the standing waves will be broken up. This is the purpose of the noise generator mentioned previously. On the basis of a 6-kc band for this noise generator, the minimum distance that can be tolerated is 12.5 cm. Actually, this figure must be modified by the fluctuation allowed in the recorded data. Another method of eliminating standing waves is to separate the instruments until the normal acoustical losses reduce the reflections to a negligible intensity.

It is important to note that the above expression for Δf provides an excellent analytical tool for certain observations and gives a basis for analyses of the geometry which is involved in a particular experimental set-up.

Standard Transducers. While the transducers have been described in detail elsewhere,[57] it is best to point out some of their novel features which are definite aids in making measurements at these frequencies.

The instruments consist of three sections: (1) sound piston and coaxial leads, (2) network housing, and (3) networks. Any one of the three parts is interchangeable with parts from other instruments. The connections between parts are kept watertight by rubber gaskets. The tops of the pipes containing the coaxial leads have coaxial jacks into which fit coaxial plugs on the bottom of the network assemblies, and the assemblies have coaxial jack outputs for connections to the junction boxes. These connections are made by means of coaxial patch cords.

The networks serve the purpose of matching the transducers to the transmission lines. There are two such networks available; one is a hydrophone preamplifier, and the other is a transformer for use with the projector. The two coupling networks have been described.

Electroacoustical Measurements

The technique of measurement with the high-frequency system parallels to a great extent those used in the lower frequency systems. However, the frequencies and wave lengths involved necessitate a

more exact control of some of the electric and acoustic parameters. These are treated in detail in the following discussion.

Adjustment and Maintenance of Electric System. After the electric system is in thermal equilibrium, the frequency scale on the oscillator must be set. As mentioned previously, this is done at only two points, 76 kc and 2 mc, and the scale is then assumed to be correct over the rest of the range.

The output level is determined by connecting the oscillator (or power amplifier, if used) to the transmission measuring set and finding the power dissipated in 72 ohms. The set is calibrated to read a specific power level of 133 db vs 10^{-16} watt, but the introduction of standardized attenuators between the source and the set allows the measurement of higher powers. The power level adjustment for the oscillator may be made at any frequency, since its output is flat within 0.15 db over the entire range. In the case of the power amplifier, which does not have a flat response, the adjustment is usually made at 50 kc.

The carrier frequency and modulation balance of the detector are then adjusted. The sensitivity of the receiving system (detector plus recorder) is adjusted at a specific frequency, usually 50 kc, since the detector does not have a flat response. This adjustment is made with the fine gain control so that, with the gain dials of the detector set at zero, the recorder reads directly the input level to the detector. The adjustment results in a full-scale deflection of the recorder for an input level to the detector of 135 db vs 10^{-16} watt. The level of any recorded signal is, then, the recorded level minus the gain of the detector as indicated by the dial settings.

With these adjustments, the equipment is ready for use but checks of this nature must be made several times each day to correct for minor changes which may have occurred.

The fact that the power amplifier and the detector do not have flat frequency characteristics entails no serious difficulty as long as the variations are recognized and corrections made. In most acoustical measurements, comparisons are made between an unknown and a standard. If the same equipment is used with each instrument, the ratio between the two response records is correct, although the actual readings are not. Only the measurement and interpretation of specific quantities, such as current to a projector, require consideration of the frequency.

Calibration of Standards. The principle of reciprocity (see Chapter 5) was used in calibrating the high-frequency standards. The actual testing procedure has already been described, so that only the precautions peculiar to this range will be treated here.

With the short waves and narrow beams involved, the hydrophone must be accurately oriented with respect to the projector and both must be rigidly clamped, as a very small movement may introduce serious errors. Care must also be taken to have the projector beam completely cover the active acoustic face of the hydrophone. It is unfortunate that, in many high-frequency units, the beam tends to wander from the established acoustic axis as the frequency is varied. This will introduce serious errors unless the hydrophone is located far enough from the projector to have only negligible variations in the portion of the field being measured. This variation in beam pattern may be detected by reorienting the projector at various frequencies and noting the change in direction of the axis. Effects such as these necessitate the complex positioning equipment.

The orientation of the projector and hydrophone is made at the highest possible frequency because of the increased accuracy afforded by the sharper beam pattern. However, the possibility of beam wandering must always be taken into consideration.

The units should be far enough apart so that corrections for spherical waves are unnecessary. (See Chapter 5.) The method of testing for this effect, and also for that of incomplete coverage of the hydrophone face by the sound field, is to take response runs at several distances. The shortest distance at which the inverse distance law holds determines the minimum testing distance that should be used.

To date, no instrument tested in the tank has necessitated spherical wave corrections. Such an instrument could be calibrated in the pier test areas which allow a much larger testing distance.

If standing waves are present between transducer faces, they can, in some instances, be eliminated by rotating the face of the hydrophone through a small angle.

In measuring the current to the projector at these frequencies, special precautions have to be taken because of the stray capacities involved. The circuit is shown in Figure 47 and it is to be noted that both leads are isolated from ground.

Even though the ground between resistor and

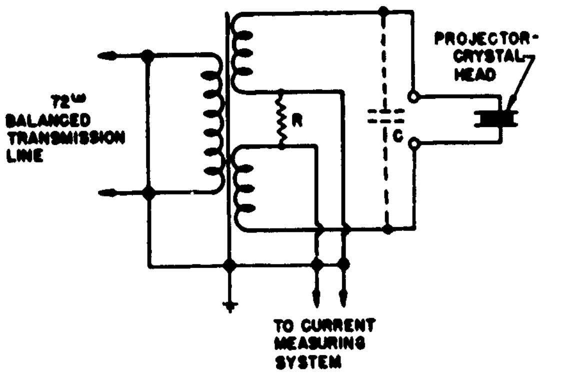

FIGURE 47. Circuit schematic for current measurements in unbalanced circuit.

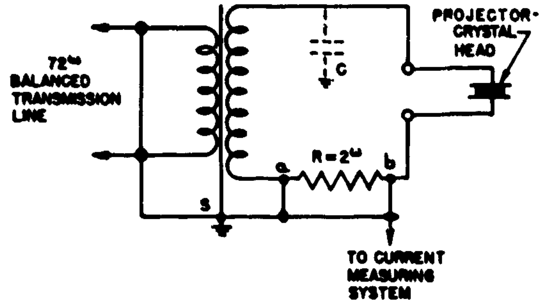

FIGURE 48. Circuit schematic for current measurements in balanced circuit.

transformer is removed, the circuit cannot be used for a projector with one side grounded because the current flowing through the stray capacity of the coil and leads will be included in the reading. For the same reason the circuit for the intermediate-frequency system shown in Figure 48 cannot be used.

Calibration of Unknown Instruments. When a set of calibrated standards is available, the calibration of unknown units is fairly straightforward. A known sound field is established between a standard projector and hydrophone. The latter is replaced by the unknown, the response of which is found in the same field. It is assumed that the unknown will satisfy the acoustic restrictions of proper beaming, absence of standing waves and reverberation, and the use of a testing distance that will not require correction for spherical waves. The sensitivity of the unknown is determined by comparison with the response of the standard, but all coupling losses are to be accounted for. If the unknown is a projector, a standard hydrophone is used to measure the sound field it generates for a given current or for given power.

Occasionally a hydrophone is found with only one high lead and the case grounded. A coupling loss measurement may be made on this instrument by immersing it in a glass container of water which insulates it from ground. However, care must be taken to avoid standing waves between the transducer head and the walls of the container.

Another case requiring special treatment is the measurement of the current to a high-impedance projector with unbalanced electrical connections. If the water resistance is high enough, the method outlined previously will give fairly accurate results if the case-to-system ground is removed. If the water resistance is not sufficiently high, recourse must be had to measuring the impedance of the projector, driving it from a known voltage and calculating the current. If the impedance of the projector is high enough, the transmission line can be terminated with a 72-ohm resistor and the projector connected across it. The voltage across the projector can be calculated then from the current through the resistor.

Greater stress has been placed upon measuring current than upon calibrating for a given available power. There are several reasons for this. The main reason is that the transformers used in coupling projectors to the line do not act like ideal transformers over this frequency range and hence cannot be represented by a voltage source in series with a resistance. This immediately destroys the concept of available power. Likewise, the power amplifier output does not conform to such a representation and so will not satisfy the conditions involved in the definition of available power. The use of a resistance pad, which would eliminate the impedance variations, would increase tremendously the size of the power amplifier, if the same power output were to be preserved. In addition to this, the problem of providing pads for various projector impedances for this frequency range is tremendous. As a result, all calibrations of projectors are at the moment made on a current basis.

The actual recording of data for all such acoustic tests follows quite exactly the procedure and printed forms used on the lower frequency systems.

FREQUENCY SCALING

The high-frequency system is admirably adapted to perform tests on scale models, with the wave length of the sound shortened on the same scale. Even meas-

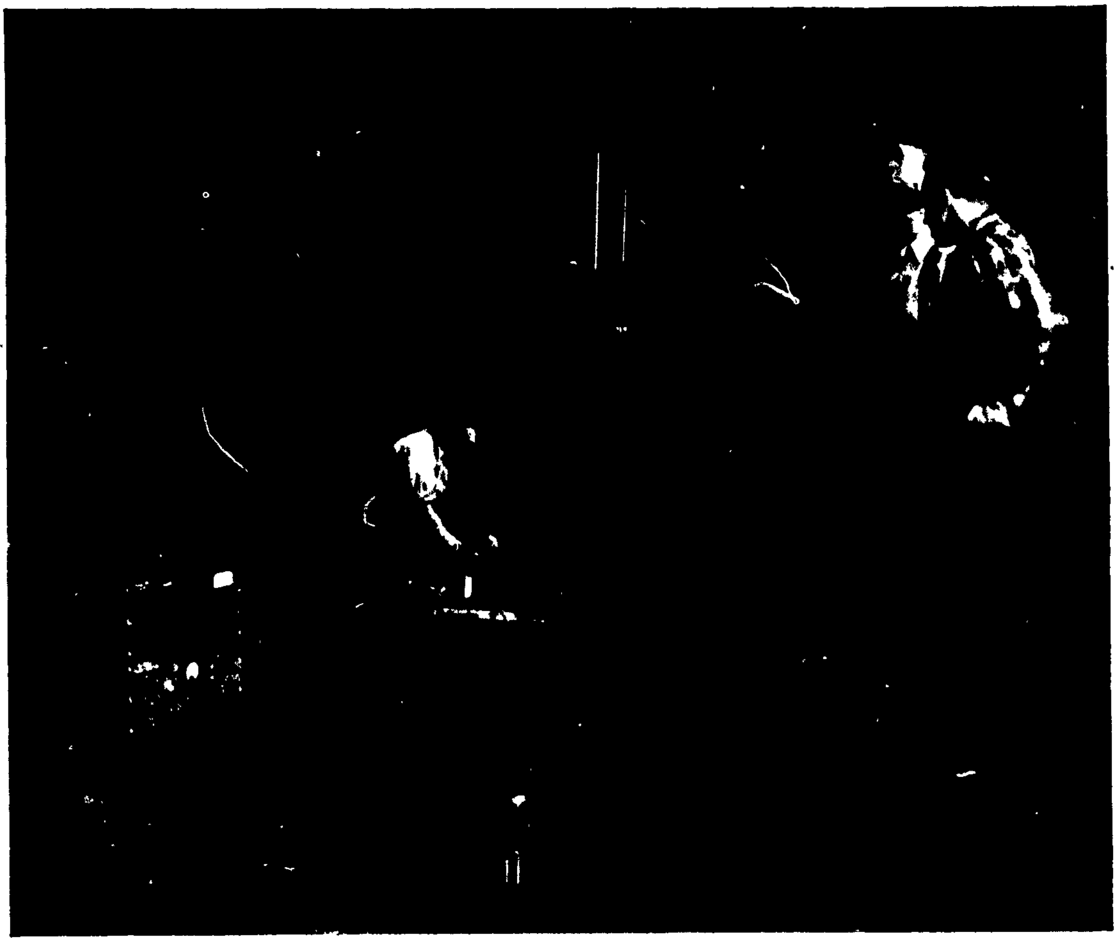

FIGURE 49. Application of high-frequency system in testing scale model submarine in outdoor test area.

urements of the reflection coefficient of such models will give a value for the reflection coefficient of the actual target. As the dimensions of the target and the wave length of the sound in actual operations are both reduced in the same ratio, all the reflection and diffraction of sound from the scale model and from the actual craft will occur in exactly the same manner.

Figure 49 shows a scale model of a submarine with all linear dimensions reduced 60 to 1. Measurements of the reflection coefficient carried out at 1565 kc give the results which would be obtained for similar measurements on the actual object at 26 kc and distances 60 times those used for the model. Sound reflected from the model is measured by an adjacent hydrophone shielded from the direct radiation of the projector. As the model is placed at several distances from the projector and rotated around various axes of symmetry, measurements of the reflection coefficient are obtained as functions of the range and the aspect of the model relative to the projector.

6.2.4 Low-Frequency Pressure System

The low-frequency pressure system at the Mountain Lakes laboratory covers 2 to 100 c and was evolved as a result of the increasing need for an accurate method of hydrophone calibration at these frequencies under controlled conditions of temperature and pressure. The system was designed and constructed by the Bell Telephone Laboratories, Inc., under NDRC contract.[49]

USES AND LIMITATIONS

The testing technique with this apparatus is independent of auxiliary hydrophone standards. The

tank consists of a rigid closed cylinder, 10 inches in diameter and 20 inches high, in which the test hydrophone is hung. A coil-driven diaphragm from an NDRC 1K projector is mounted in the chamber wall and produces high sound pressures of known magnitude in the water-filled chamber. The sound pressure is dependent mainly on the force factor of the sound source and on the mass and stiffness reactances of the diaphragm and the enclosed water. The chamber and the circular sound source and mounting are shown in Figure 51. The chamber and source together meet the requirements of a stiffness-controlled system operating over a fairly wide range of low frequency. The limitations of the chamber and the associated electrical circuit are such that the effective range over which accurate calibrations of "hard" (essentially incompressible) hydrophones may be made, lies between 2 and 100 c. Calibrations can be made only on hydrophones which are sufficiently hard not to lower the system stiffness appreciably. Reduction of the system stiffness lowers the resonant frequency and, consequently, the upper limit of the frequency range through which calibrations may be made.

Facilities are incorporated to obtain measurements at temperatures between 35 and 100 F and at pressures up to 100 pounds per sq in. The use of a closed testing chamber permits measurements of the dependence of a hydrophone upon temperature and pressure to be made more conveniently than under free field conditions. Approximately six hours are required to obtain a characteristic frequency response over a complete temperature cycle at each hydrostatic pressure.

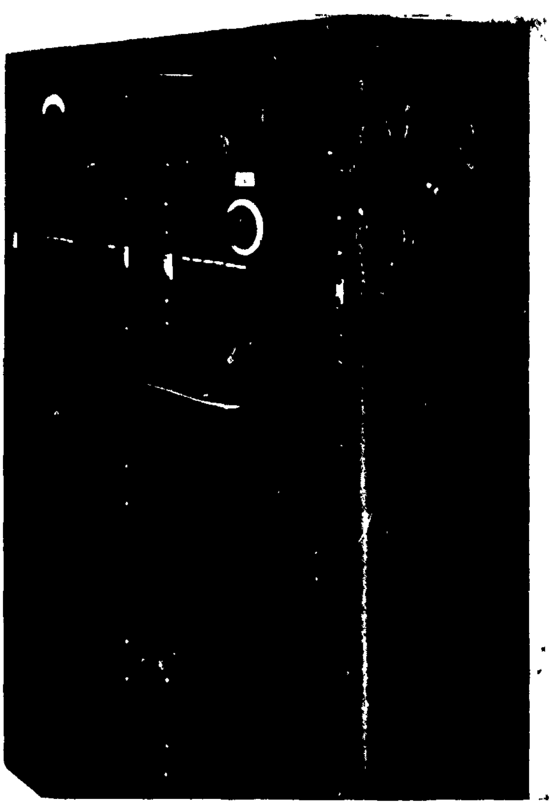

FIGURE 50. Electrical equipment of low-frequency system.

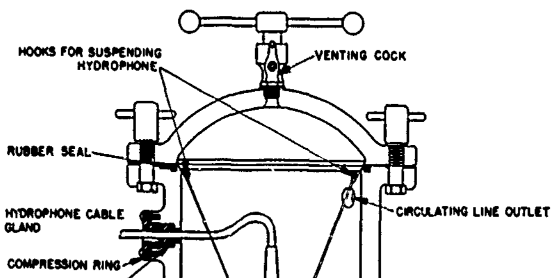

FIGURE 51. Calibration chamber section of low-frequency system tank, showing sound source and other details.

Hydraulic System

A schematic diagram of the hydraulic system appears in Figure 52.

Calibration Chamber. The chamber consists of two bronze castings 1 inch thick, together weighing about 500 pounds. The dimensions and construction are shown in Figure 53. The strength and size are such that no chamber or wall resonances occur below 200 c. The resonant frequency of the sound source is well above 250 c.

Since even small quantities of air greatly reduce the chamber stiffness, provisions have been made for deaerating the water by reduced pressure and also for air venting of the chamber. The shape of the chamber was designed to facilitate the removal of air, and the direction of the water flow is such that air is carried

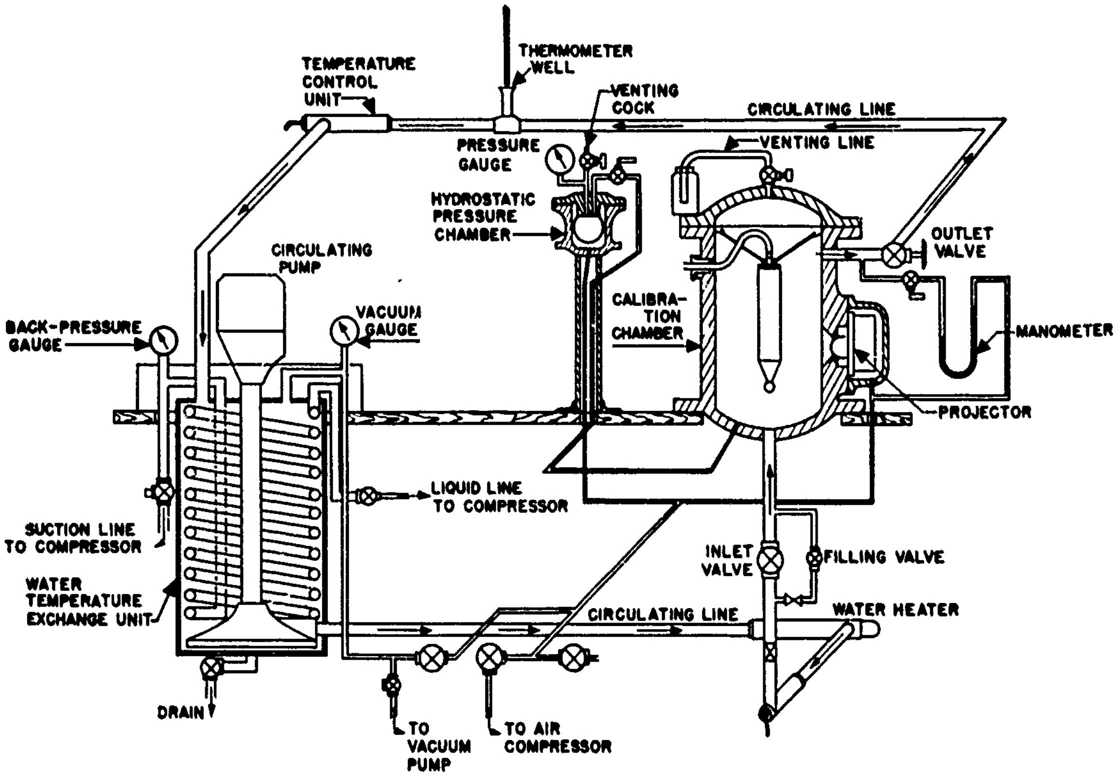

FIGURE 52. Operating schematic of hydraulic arrangement for low-frequency system.

to the venting cock at the top. When the system is freshly filled, the water may be heated and circulated under vacuum to decrease the amount of air in solution, though the chamber and instrument are carefully debubbled by hand before each test.

Hydrostatic Pressure Chamber. Hydrostatic pressures up to 100 pounds per square inch are obtained by the use of air from a small compressor unit. The pressure is transmitted through a moulded rubber bag of negligible stiffness, mounted in a bronze chamber. As may be seen in Figure 52, the water side of the bag connects to the calibration chamber through a line with high acoustic impedance. The air line connects to both the pressure chamber and the rear chamber of the sound source through suitable control valves, thus equalizing the pressures on the sound source diaphragm. A manometer is connected to the system in such a way that the pressure differential may be checked at all times. Since there is need during a hydrophone calibration to read the mercury column to within ±0.1 mm, an optical system was used which allows displacements of less than 1 cm to be read within ±0.05 mm without parallax.

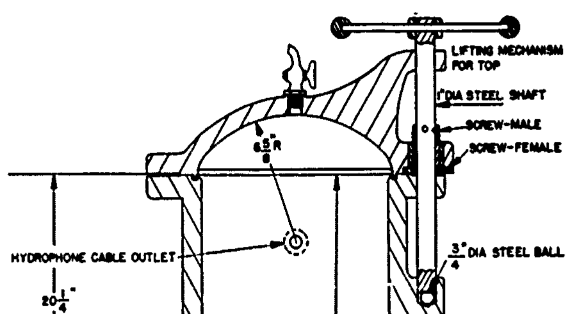

FIGURE 53. Calibration section of low-frequency system tank, showing top lifting mechanism and major dimensions.

Equipment for Cooling, Heating, and Circulating the Water. The water line from the test chamber leads to a 13x25-inch pressure tank in which are sealed the impeller of a circulating pump and the evaporating coils of a cooling system. A 2,000-watt, 110-volt immersion heater is located in the line returning from the tank to the test chamber. Control facilities enable the system to be held within 1 degree of any desired temperature.

Temperature reduction is accomplished by an air-cooled Freon compressor with 1½-hp motor. A close control of temperature in cooling is obtained by using the heater in conjunction with the refrigerating unit. Safety controls are incorporated which prevent the system from either freezing or rising above 105 F.

Circulation is maintained by a rotary pump of ¼ hp while the temperature is being changed, but when the desired value is reached the circulation is stopped and the test chamber closed off by valves.

The water is deaerated by a vacuum pump with a ⅙-hp motor.

Electrical System

The apparatus consists of an oscillator, power amplifier, variable attenuator, and receiving amplifier and level indicator. Figure 54 shows the connections in a typical testing setup. The units which are permanently installed are mounted in bays adjacent to the hydraulic system. For flexibility and ease of operation, the equipment is terminated in several jack strips.

The signal generator is a Hewlett Packard audio oscillator, Model 202DR. It imposes the lower limit of 2 c on the system. Sound pressures up to 10^5 dynes per sq cm may be used at any point in the frequency range.

The power amplifier was designed especially for low frequency. It operates on alternating current and has a maximum output of 6 watts. The gain may be controlled over 45 db in 5-db steps with continuous adjustment through each step. The circuit has been equalized to give a frequency response which is flat to 0.1 db over the working range. The input and output impedances are 600 ohms and 50 ohms, respectively.

The attenuator provides 45 db in 1-db steps giving a dial which reads hydrophone responses directly from −80 to −125 db vs 1 volt per dyne per sq cm when the chamber stiffness is 10^8 dynes per cm.

The component parts of the receiving amplifier

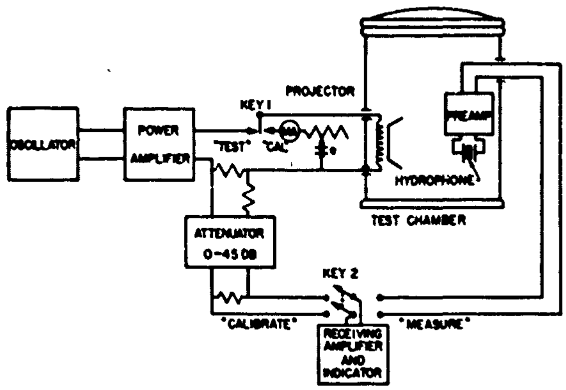

Figure 54. Electrical measuring circuit used with low-frequency system.

and indicator are the amplifier, a copper oxide rectifier, and a meter reading from −10 to +10 db. Input impedances of 80,000 ohms unbalanced, and 600 ohms balanced or unbalanced, are available. The gain is essentially flat over the range of 2 to 100 c. The dial of the amplifier-gain control covers 50 db in 5-db steps so that its setting plus the meter reading gives the input signal level into the 600 ohms in db vs 10^{-16} watt. With a fixed 20-db gain which may be added, a range from 50 to 120 db can be read directly.

Two combinations of capacitors and resistors are available for insertion in the meter circuit. For frequencies up to 10 c, the one with the larger time constant is selected to give a fairly steady meter deflection. At higher frequencies, the lower time constant is chosen to increase the rate of meter response.

Procedure

The stiffness of the chamber must be measured over the whole range of both pressure and temperature since it enters as a correction in all determinations of hydrophone sensitivity. The procedure is to close key 1 (Figure 54), thus putting a small direct current through the projector coil and producing a pressure indicated on the manometer. From this measurement and known diaphragm constants, the stiffness may be computed. Extensive computations are obviated by the use of a chart relating these factors.

The system is thus calibrated so that the sound pressure in the chamber is known for any projector current at any point in the range of stiffness. Thus the sound pressure which produces the measured output voltage of the hydrophone could be calculated

from the projector current but the circuit is arranged to save the calculation and calibrate the hydrophone in absolute units. With key 2 in one position, the meter is connected to the hydrophone and deflected by its output voltage. With the key reversed, the meter is across a resistor carrying the projector current which produces the sound field. The attenuator is then adjusted until the meter reads the same as when connected to the hydrophone. As the position of the attenuator is related to the sound field and its output voltage matched to that of the hydrophone, it may be calibrated to read the sensitivity of the hydrophone directly in units referred to 1 volt per dyne per sq cm for the normal tank stiffness of 10^8 dynes per cm. Corrections for other values of the stiffness are taken from a chart.

6.2.5 High-Power System

The high-power amplifiers at the Orlando and Mountain Lakes stations have approximately the same electric characteristics. The overall gain of each amplifier is about 24 db and the response is flat within 1.5 db from 1 to 100 kc. At the extreme ends the response falls off, 4 db at 150 kc, 10 db at 200 c. The amplifiers should not be driven at high powers below 200 c because of increased coil losses.

The output impedance is 100 ohms; the input may be either 135 or 600 ohms. The power available with a minimum of distortion is 1,200 watts but 1,500 may be obtained with a slight increase in harmonic content.

Each system is provided with a repeating coil that will match the line of impedance of 100 ohms to a 50-, 100-, or 500-ohm load. In addition, there is a 30-db pad capable of dissipating 1,500 watts and having a 100-ohm input and a 135-ohm output to match the repeating coil to the transmission measuring set. At both stations the pads and repeating coils are mounted in the transmitting booth and the connections appear on a coaxial jack strip in the booth.

It is obvious that care has to be exercised in the choice of lines and switching elements for currents that may reach 6 amperes and potentials as high as 500 volts. It has been found that the lead-covered coaxial pier lines and the coaxial jacks handle these powers satisfactorily but special patch cords had to be constructed to provide connections of adequate capacity. The plan of using patch cords and jack strips at these powers involves the danger of disconnecting the high-level side when in use. Large arcs may result and the damage to the jacks and terminals will be minor compared to that which may occur from the overload voltage developed in the final stage of the amplifier. With this in mind, particular attention is given to the location of the jacks, and special lines are run whenever possible. Warning signs are kept at the critical junction points.

The connections from the intermediate-frequency systems to the low-level input of the power amplifier are made in a jack field associated with the amplifier. No caution is needed for these connections, as breaking them under load causes no damage.

In using the amplifiers, power-level measurements are made in two ways. The first involves a 30-db pad and the transmission measuring set to determine the available power for the 100-ohm output. The second requires either a thermocouple wattmeter or a recording wattmeter to measure the power delivered to the load. Apart from the precautions needed for the high powers involved, these amplifiers are treated merely as extensions to the existing equipment.

In their electrical details the amplifiers at Orlando and at Mountain Lakes differ considerably. While both are essentially two-stage, push-pull, transformer-coupled units, the power requirements are quite different.

The Orlando amplifier is a Navy echo-ranging type in which the input, output, and interstage transformers are replaced with special transformers designed for the particular frequency and power range. However, the power supply and control circuits are retained and these require a 3-phase, 440-volt, 60-cycle supply. Since this is not available from the power lines, a motor-generator set was used with 6-kva maximum output.

To compensate for fluctuation of line voltage, internal impedance of the generator, and other sources of instability, an electronic regulator is used which maintains the peak voltage within 1 per cent. Control of the peak is chosen because the critical voltages in the amplifier are determined by the peak of the supply rather than by the rms value. Because of the change in wave form, the rms value shows a variation of 5 per cent from no load to full load for a peak variation of only 1 per cent. Another reason for controlling the peak voltage is the speed of response which in this regulator will compensate for any changes in a few cycles. Adjustments are also made to prevent hunting. Such adjustments are very necessary with rotat-

FIGURE 55. Electrical equipment of high-power system.

ing machinery of this size in order to realize the point of greatest stability.

The Mountain Lakes amplifier operates at 220 volts directly off the single-phase, 60-cycle supply. It differs from the Orlando unit in that all grid-supply voltages are regulated quite closely since the grid currents may rise to 20 or 30 milliamperes in the final power stage.

The amplifier at Mountain Lakes is shown in Figure 55. The bay appearing at the side is used for terminating crossties to the other systems and for connections to the amplifier. In this bay are also a master intercommunication station, attenuators, and a separate signal source (Western Electric Company 17B oscillator). Plans are being considered to incorporate in this bay a generator and transmitter modulator with longer pulses than are now available. This pulsing equipment would be used with the power amplifier to simulate actual operating conditions in echo-ranging systems. The arrangement would allow projector characteristics to be measured under typical working conditions. This is of particular importance in the study of cavitation and of heating due to power losses on the transmitting efficiency.

6.2.6 High-Pressure System

Measurements on transducers operating in the intermediate-frequency range and under hydrostatic pressure up to 300 lb per sq in. may be made in the high-pressure tank. The pulse system is used to overcome the difficulties of testing in a confined medium but there are still limitations as to what can be tested in the tank.

Description of High-Pressure Tank

The tank, made of 1$\frac{3}{32}$-inch firebox steel, is a horizontal cylinder 8 feet in diameter and 14 feet long. There are eight glass-covered viewing ports along the sides of the tank. Two ports on top provide access to the interior. One port is oval in shape, being 1 foot wide and 3 feet long. It is provided with a 2½-inch thick steel cover. The other port is circular and has a diameter of 2 feet. Built as an integral part of the cover of this port is a single shaft rotator, similar to the rotator described in connection with the intermediate system. This rotator can be used in conjunction with the polar recorder turntables of either intermediate-frequency system. The shaft of the rotator passes through a pressure gland in the center of the cover. The circular port is located 4½ feet from one end of the tank and the oval part is located 3½ feet from the other end. Baffles of 1-inch steel plate have been placed at the center of the tank as shown in Figure 61, leaving a square aperture 3 feet by 3 feet. An overhead monorail and hoist system is used to handle the heavy port covers and test instruments.

Rails for a carriage from which to suspend transducers are mounted in the tank under the oval port. The carriage is controlled by two threaded rods that pass through stuffing boxes in the end of the tank and terminate in hand cranks. One rod moves the car-

FIGURE 56. View of high-pressure tank, showing side viewing ports.

FIGURE 57. View of oval port of high-pressure tank.

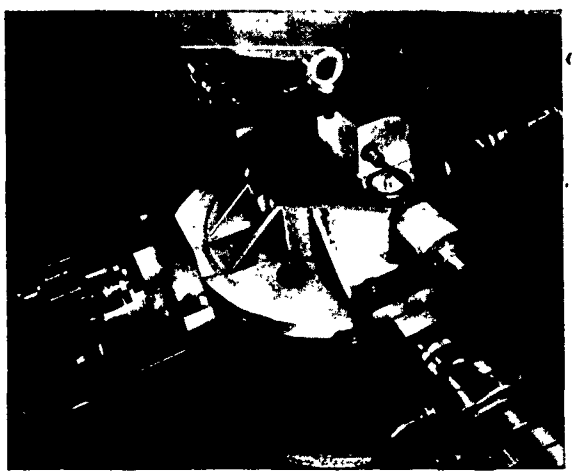

FIGURE 58. View of circular port of high-pressure tank.

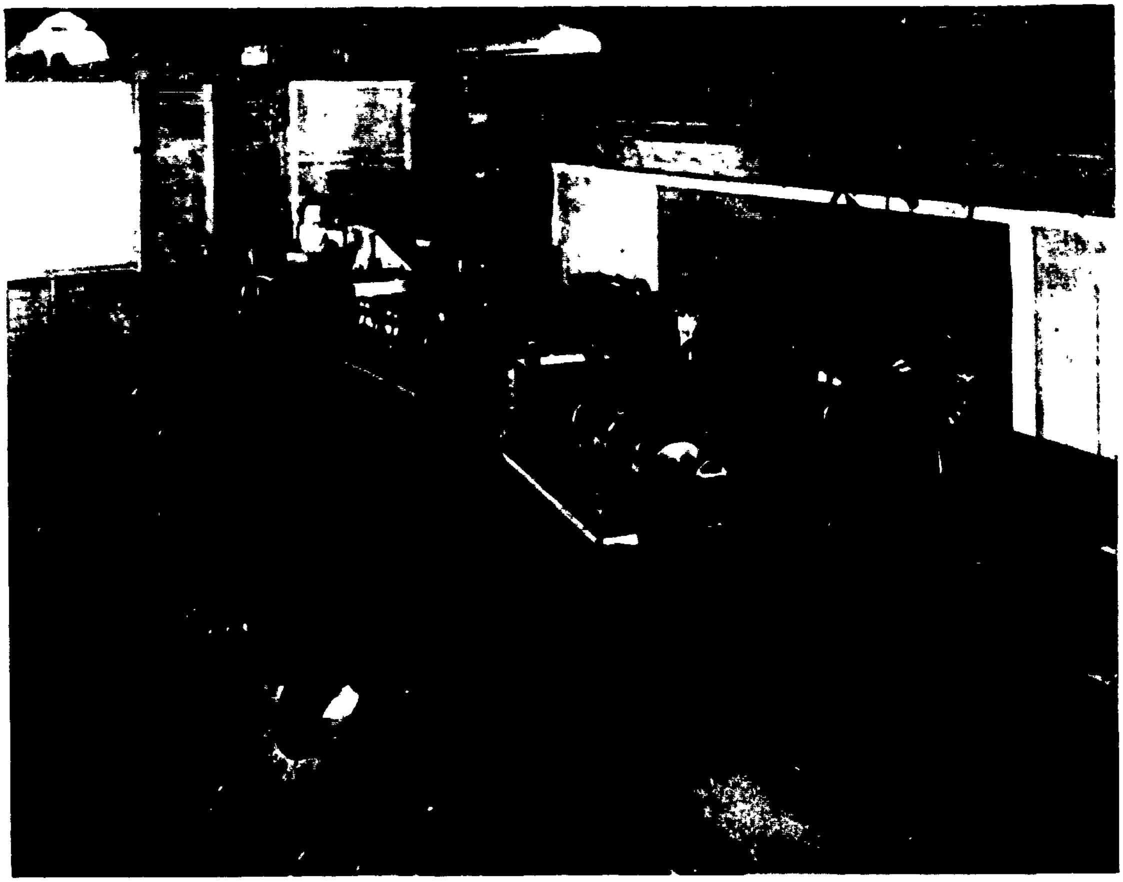

FIGURE 59. View of high-pressure tank, showing top working area.

riage lengthwise of the tank and the other rotates it about a vertical axis through a maximum of 30 degrees. The travel of the carriage allows the distance between two transducers to be varied from 4 to 8 feet.

Each port cover is held securely in place by four hydraulically operated wedges, constrained in the vertical direction by bridges. Each wedge, cut at an angle of 10 degrees, exerts a downward force of 60,000 pounds on the cover when actuated by a hydraulic cylinder operated at a fluid pressure of 1,000 pounds per square inch. The hydraulic system for operating the wedges is shown in Figure 60. The hydraulic system pump is equipped with a 1,000 pounds per square inch automatic by-pass and can deliver 3 gallons per minute at this pressure.

The tank is filled directly from the lake and, since it is drained frequently, no provision is made for inhibiting the growth of organisms except that several chemical briquettes like those used in the high-frequency system are left in the tank to dissolve. The system for filling and applying pressure is shown in Figure 61. A pump with a capacity of 1,500 gallons per hour is used for filling the tank and, when necessary, for circulating the water through a heat exchanger coupled to the heating system of the laboratory. With all valves closed, the pressure is applied by a high-pressure pump governed by an adjustable pressure switch. The control is automatic and will keep the pressure at any value up to 300 lb per sq in. within ± 5. Two safety valves protect the system from excessive hydrostatic pressures.

The interior of the tank has been coated with the bubble layer developed by the Massachusetts Institute of Technology in order to obtain some sound absorption at the walls.

Acoustic Measurements in High-Pressure Tank

Acoustic measurements in the tank differ from those in a free field because of the relatively small size

of the tank and the absence of perfectly absorbing walls. The limitations imposed by the relatively short testing distances and the use of pulsing to make the measurements independent of reflection have been discussed in Chapter 5.

In actual testing, the optimum values of testing distance and pulse length being somewhat interdependent within certain limits, the distance may be increased by using shorter pulse lengths and vice versa. Larger test distances may be used with transducers of good transient response than with sharply resonant ones. A pulse of 1.8 milliseconds is permissible when the test distance is 5 feet because of the baffles which prevent reflections from the sides of the tank. Without baffles the reflections would be delayed only some 0.8 milliseconds. At the maximum distance of 8 feet, the permissible pulse length is 0.4 milliseconds. For many transducers these distances and pulse lengths give results equivalent to those in a free field. Even when the tank will not permit such equivalent calibrations, it should be possible to observe the relative performance of transducers as functions of temperature and hydrostatic pressure. Observation of these functions is obviously not possible with tests made in the lake.

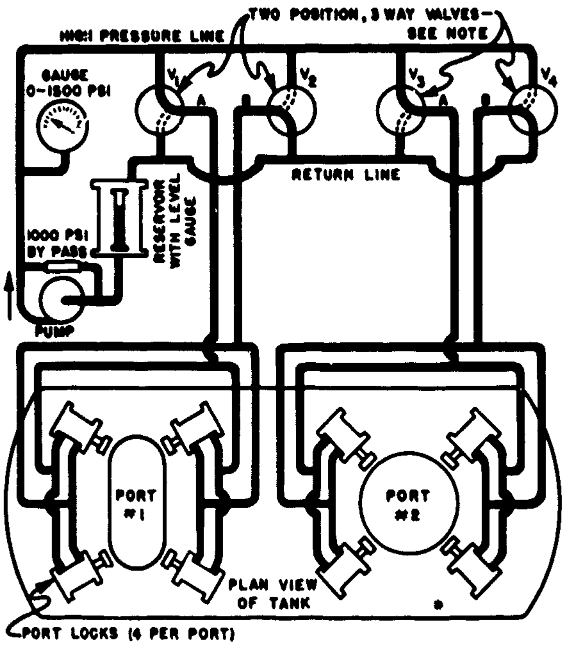

FIGURE 60. Hydraulic system for holding port covers on high-pressure tank.

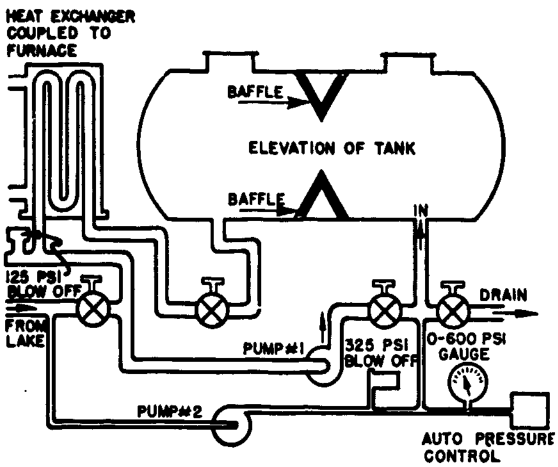

FIGURE 61. Hydraulic system of high-pressure tank. Pump No. 1 is used for filling tank and circulating water through heat exchanger. Pump No. 2 applies pressure to tank when all valves are closed.

The cleaning, rigging, and debubbling preparation of the transducers is identical with that for the free field testing, with the added precaution that the instruments must be capable of operating at the desired test pressures. The available power is measured with the 30A set, with the transmitter modulator of the pulse system arranged for continuous-wave output. By the nature of the modulator circuit, the same instantaneous value of power is maintained when it is switched to the pulsing operation.

Observation on the cathode-ray oscilloscope [CRO] allows rapid adjustment for the proper pulse length, delay time, and received pulse. The recurrence rate is set so the reverberation from one pulse does not interfere with the measurement of the succeeding pulse.

6.2.7 Noise and Transient Measurements

As pointed out in Chapter 5, acoustic noise may be classified, for the purpose of analysis, as continuous, such as thermal or cavitation noise, or as intermittent, such as waves of explosive origin. The method used in measuring continuous noise has been treated under the description of the intermediate-frequency system (15 c – 150 kc) in Section 6.2. None of the methods described previously is suitable for intermittent sound.

ANALYSIS AND MEASUREMENT OF TRANSIENTS[61]

Transients may be considered as composed of sinusoidal signals having a continuous distribution in

frequency and may be represented by the Fourier integral:

$$E(t) = \int_0^\infty A_f \sin(2\pi f t - \alpha_f)\,df, \qquad (1)$$

where A_f and α_f are the amplitude and phase of each component frequency and E (t) gives the time variation of the resultant pulse amplitude and phase. For most practical work only the dependence A_f on frequency need be determined.

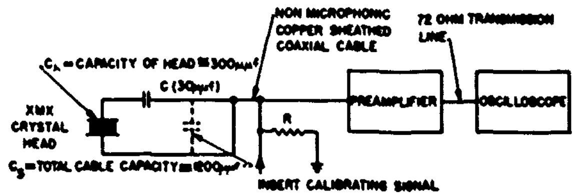

FIGURE 62. Schematic of circuit used in measuring transients.

One method of obtaining this information about a transient is to make a record of its wave form and analyze it. This technique may be used on high crest-factor noises which cannot be analyzed with the usual electric and recording systems.

A schematic of the electric circuits for detecting and recording transient wave forms of high peak pressure is shown in Figure 62. A transducer is used to convert the acoustic pressure to an equivalent voltage which is amplified and impressed on a cathode-ray oscilloscope producing a beam deflection proportional at each instant to the acoustic pressure. By photographing the oscilloscope screen on a motion-picture film travelling at constant velocity, a record of the transient wave form in amplitude and duration is obtained. For accurate reproduction of the acoustic transient, the phase distortion and frequency discrimination must be kept to a minimum.

A transducer with the XMX crystal head is selected primarily because of its small size and uniform frequency response. However, since this head has an x-cut crystal of Rochelle salt, it is necessary that it be terminated in an impedance much higher than its own to minimize the effect of temperature. Because of microphonic effects, it is necessary to place all electronic equipment a considerable distance away, preferably out of the water entirely. This involves long leads to the preamplifier. To prevent the hydrophone from becoming temperature-dependent because of the capacity of the connecting cable, a very small nonmicrophonic capacity (C in Figure 62) is connected in series with the crystal head at the junction of the head and connecting cable. This is in effect a capacitative voltage divider with an input impedance high compared with the XMX head. As a divider it has good phase and frequency characteristics as long as any resistive components involved are high compared with the shunt capacitative reactance. It is also to be pointed out that any external capacity shunting the cable capacity will further increase the voltage division. The voltage-dividing effect of the network serves a second essential purpose in reducing the peak voltages resulting from high peak pressures to the point where they are on the linear portion of the preamplifier curve. The combination of crystal head, voltage-dividing network, and cable is treated as a unit and all acoustic calibrations are referred to the end of the cable.

The preamplifier serves also as an impedance transformer to provide a 100-megohm impedance to the hydrophone and 72 ohms to the transmission line. Two such preamplifiers are available, one with a gain of −11 db for high sensitivity heads, such as the XMX type, and one with a gain of 35 db for low sensitivity heads, such as tourmaline types. Both have a flat response and a linear phase-frequency characteristic from 2 c to over 600 kc. For almost all measurements of transient phenomena, as well as those with high peak pressures, this laboratory has used the XMX head in conjunction with the first preamplifier.

The oscilloscope used for these measurements is a Dumont type 247 provided with an external supplementary intensifier voltage for more brilliant traces.

The records of the wave form were made on a moving film camera (Western Electric Fastax) with film speeds up to 100 feet per second. Theoretically, frequencies as high as 600 kc may be resolved at this speed. The camera was used without the shutter mechanism. With the moving film, no horizontal sweep signal or transient sweep circuits are used in the oscilloscope but the vertical amplifier which multiplies the voltage from the transient is essential.

It is perhaps best to point out here that, while all the electronic equipment was constructed with linear phase-frequency characteristics over the entire range of 2 c to 700 kc, the phase characteristics of the hydrophones are not entirely known. In general, if a hydrophone does not have any rising sensitivity with frequency and if there are no "breakups" in the response

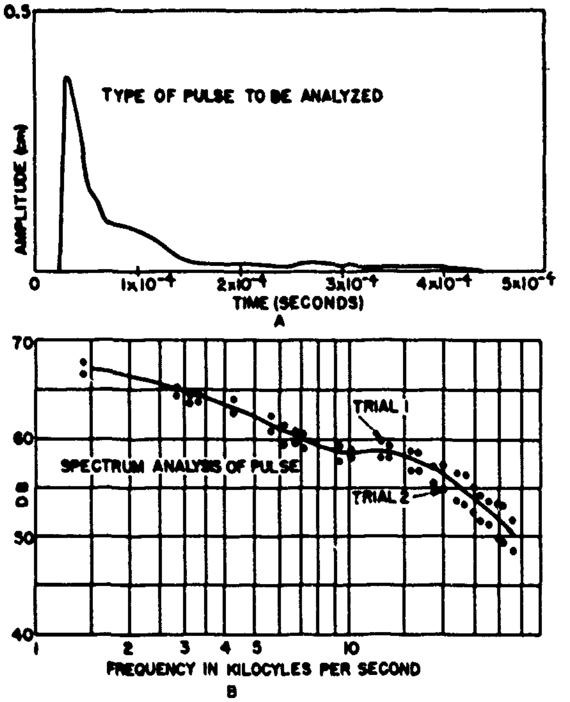

FIGURE 63. Transient analysis of explosive wave form.

curve, it may be assumed that the phase relation is fairly linear. This assumption should be further investigated. However, the phase-frequency characteristic does not affect the amplitude-frequency analysis of the transient but only affects its wave form.

The frequency analysis of the transient is made from the photographic record by the use of a harmonic analyzer. The USRL was fortunate in having the use of a Henrici Analyzer,[58,79] through the cooperation of the Department of Physics, Case School of Applied Science. This analyzer gives the relative amplitudes of thirty harmonics. A complete frequency analysis of a transient requires from several hours to several days, depending on the complexity of the transient. The resultant data are then only relative and require supplementary computations for conversion to actual units such as pressure and frequency. A sample analysis of an explosive wave by this method is shown in Figure 63. The analysis gives the rms pressure in db vs 1 dyne per sq cm in a 1-c band as a function of frequency.

6.2.8 Auxiliary Laboratory Equipment

Considerable auxiliary equipment is needed in the calibration and maintenance of the measuring systems as well as in the calibration of transducers. For convenience in description the apparatus is divided into six groups: resistance and impedance bridges, test meters, portable signal generators, cathode-ray oscilloscopes, wattmeters, and miscellaneous equipment.

Resistance and Impedance Measuring Bridges

The laboratories are provided with a number of admittance and impedance bridges suitable for measurements over a wide range of values with the various frequency ranges.

The *Western Electric Company 5A Impedance Bridge*[1] is used in the frequency range 1 to 150 kc. It is an admittance bridge of the comparison type, measuring impedance in terms of the equivalent parallel resistance and capacitance components. It permits measurements on devices which are electrically balanced or unbalanced to ground. It measures parallel resistance components up to 1,100 ohms directly with supplementary computation to 1 megohm. Parallel capacitance (or inductance considered as negative capacitance) may be measured directly up to 0.11 μf, and above this value by the addition of external capacitance. The bridge is designed for an overall accuracy in impedance determinations of ±0.5 per cent, but it has reduced accuracy for extremely high parallel resistive components. It is ordinarily used with a 17B oscillator and a 31A transmission measuring set detector described later in this section. A typical arrangement of these devices can be seen in Figure 4.

The *Bell Telephone Laboratories W-10134 Impedance Bridge* consists essentially of two units, a capacitance comparison bridge and a Maxwell inductance bridge, thereby obviating the computations necessary to convert parallel values to series values or vice versa. The use of the bridge is limited to electrically unbalanced instruments and a frequency range of 200 c to 150 kc. The comparison bridge measures capacitances from 0.1 $\mu\mu$f to 1.11 μf and conductances from 0.01 μmho to 111,100 μmhos. The Maxwell bridge measures inductances from 0.1 μh to 1.11 h and resistances from 0.01 ohm to 111,100 ohms. The accuracy of direct bridge readings is approximately ±1 per cent. Complete operating instructions and descriptive material are available which give correction factors to obtain a precision of ±0.1 per cent.

To facilitate impedance measurements at the testing area, this bridge, together with a 17B oscillator

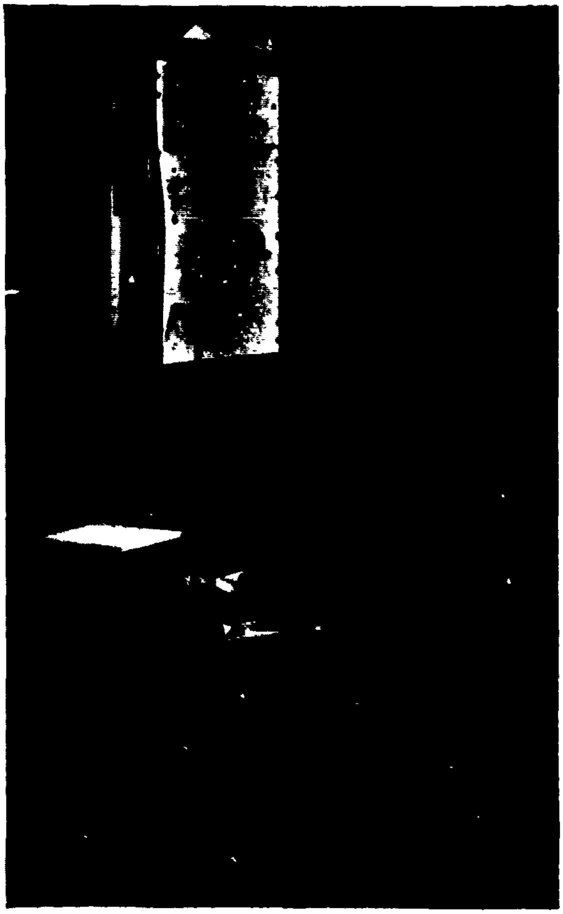

FIGURE 64. Making impedance measurements using the W10131 impedance bridge, the 31A detector, and the 17B oscillator.

and a 31A transmission measuring set, is mounted on a rack equipped with casters. See Figure 64.

The *W-10093 Capacitance and Conductance Bridge* for measurements at high frequencies was constructed by Leeds and Northrup Company, Inc. in accordance with a design by Bell Telephone Laboratories. The normal frequency range is 50 kc to 5 mc but it may be used as low as 10 kc and as high as 10 mc without serious loss of sensitivity or accuracy. The capacitance range is from 0.01 to 1,100 $\mu\mu$f either positive or negative and the range may be extended well beyond 11,000 $\mu\mu$f by means of five plug-in standards. The conductance range is from 0.001 to 1,100 μmhos and may be extended to 11,000 μmhos and further by plug-in standards. Both types of measurement may be extended even further by connecting a known admittance in series with the one to be tested. For the normal frequency range the accuracy is about 0.25 per cent.

The *General Radio Company Impedance Bridge Model 650A* is a direct-reading instrument with a self-contained battery and a 1,000-c oscillator. It gives quick approximations of impedance at 1,000 c or with direct current. It gives d-c resistances from 1 ohm to 1 megohm, capacitances from 1,000 $\mu\mu$f to 100 μf, and inductances from 1 μh to 11 h.

A *Leeds and Northrup Company Wheatstone Bridge* is used for precise d-c resistance measurements.

Test Meters

The meters used at the laboratories are standard ohmmeters and voltmeters with the exception of a special megohmmeter and a 31A transmission measuring set. Several portable Simpson and Weston volt-ohm ammeters are used in the maintenance of the electronic equipment and in making the customary electrical checks on transducers. A number of electronic voltmeters are used for measurements where the test meter must have a high impedance.

A *Ballantine a-c Voltmeter* measures rms voltages from 0.001 to 100 volts over a frequency range of about 10 to 150,000 cycles with a general accuracy of 2 per cent. When used in conjunction with a decade amplifier, measurements may be made considerably below a millivolt with frequencies from 10 to 100,000 c. The use of a special multiplier extends the upper limit to 1,000 volts.

The *Hewlett Packard Vacuum-Tube Voltmeter, Model 400A,* is used extensively for relative measurements of rms voltages between 0.03 and 300 volts over the frequency range 10 c to 1 mc.

The *Measurements Corporation Electronic Voltmeter, Model 62,* provides ranges of 1, 3, 10, 30, and 100 volts with an accuracy of 2 per cent of the full-scale reading. When used with its associated probe, it allows measurements from 30 c to 150 mc. It should be noted that it reads peak voltages. A specially designed *vacuum-tube thermocouple voltmeter* was constructed by USRL for rms voltages.

A special *Rawson Electrical Instrument Company Megohmmeter* is used primarily for measuring insulation resistance at 2,500 volts and covers 0 to 100 and 0 to 10,000 reading directly in megohms.

A *Western Electric Company 31A Transmission Measuring Set* is used extensively as a null indicator for the various impedance bridges. The high sensitivity and frequency discrimination provide excellent

FIGURE 65. W10093 capacitance and conductance bridge for use at high frequencies.

resolution in balancing under severe conditions of wave distortion. The set consists of an amplifier with calibrated gain controls, an oscillator and modulator circuit operating in conjunction with a 20-c band-pass crystal filter, an output meter, and a regulated d-c supply circuit operated on 115-volt, 60-c power. The set has been designed to operate through the frequency range 1 to 150 kc with switches to permit its use as a wide-band or a sharply tuned instrument. Continuous tuning control from 10 to 150 kc is effected by the frequency adjustment of the local oscillator.[62]

Portable Signal Generators

The *Western Electric Company 17B Oscillator* is a heterodyne type operating on 60-c power and delivering levels up to 160 db vs 10^{-16} watt into a 135- or 600-ohm load and over a frequency range of 1 to 150 kc. Below 1 kc the power output decreases and the wave form becomes poor. It is used extensively in impedance measurements because of its highly stable and uniform output level, accurate frequency calibration, and low harmonic distortion.

The *Hewlett Packard Oscillator, Model 200-Cr* covers a frequency range of 20 c to 200 kc. It is designed to deliver a signal level of 150 db vs 10^{-16} watt into a 1,000-ohm resistive load, although its output is not critically affected by the loading. The total harmonic distortion, under proper operation, is less than 1 per cent.

The *Measurements Corporation Square Wave Generator, Model 71*, permits rapid determination of the phase and frequency characteristics of many types of amplifiers and networks when used in conjunction with a cathode-ray oscilloscope. The time of rise on the wave is about 0.2 microsecond with frequencies from 5 to 100,000 c. The Fourier analysis of these waves shows components that give a resultant range of investigation from 1 c to several megacycles.

The *Dumont Electronic Switch and Square Wave Generator, Type 135A*, produces square waves at 10 to 500 c with a form that reaches full amplitude within a few microseconds. In addition to its usefulness in studying the performance of amplifiers and other networks, it may be used in conjunction with a cathode-ray oscilloscope to make comparison studies of amplitude, wave form, phase, and frequency between two electric signals.

Cathode-Ray Oscilloscopes

Practically all measuring circuits require cathode-ray oscilloscopes. *Dumont Type 175A* is used to provide visual monitoring in each of the 15-c to 150-kc test systems. A *Dumont Type 247* is used with an auxiliary circuit supplying higher accelerating potentials for special studies of transients requiring high-speed oscillograms.

A *Renier Model 556* operates at frequencies up to 4 mc and is useful for observing wave forms at the higher frequencies and for observing carrier modulator balance.

Wattmeters

A thermocouple wattmeter and a recording-type wattmeter have been developed by the laboratories for the measurement of power over the large frequency range used in underwater acoustics. The two operate on different principles and the second was particularly designed to be used in conjunction with the present electrical systems.

Thermocouple Wattmeter.[54,50] As the circuit of the thermocouple wattmeter shows in Figure 66, the instrument can measure current and voltage as well as power. The measurement of these three quantities allows a calculation of the load impedance. Other features of the design are that the power range switch tends to keep the impedance range of the instrument constant and that the power measurement is independent of wave form.

This meter is designed to operate for load impe-

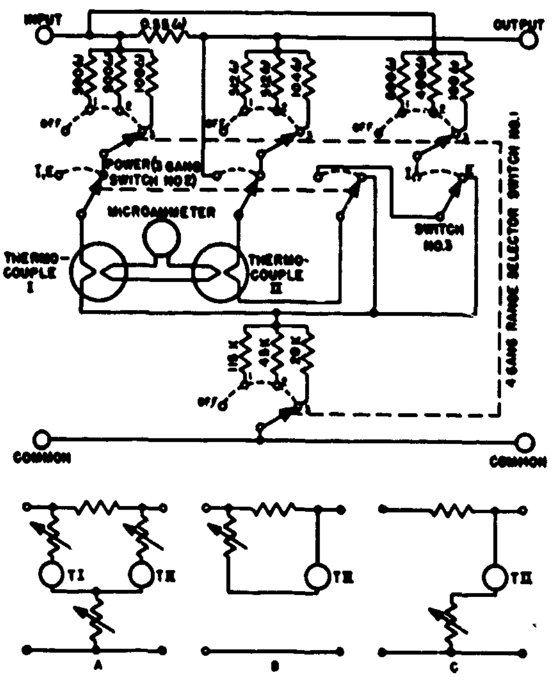

FIGURE 66. Circuit schematic of thermocouple wattmeter; circuit arrangements are shown for: (A) power measurement, (B) current measurement, (C) voltage measurement.

dances from 10 to 300 ohms and has power scales of 100, 500, and 1,000 watts. The indicated and ac ual scale factors agree within 1.5 per cent from 0 to 100 kc. Operation outside the impedance limits will not only affect the accuracy and overload the thermocouples but even may destroy them.

While the thermocouple wattmeter is direct-reading and fairly accurate, the time required to reach temperature equilibrium delays the readings so that point by point measurements are required. The possible destruction of the thermocouples from sudden changes in load impedance and the limited impedance range for any one power scale are distinct disadvantages. The recording wattmeter was designed to overcome these difficulties.

Recording Wattmeter.[66] In measurements with the recording wattmeter, two signals designated Σ and Δ are obtained and recorded. The signal Σ is obtained by adding a signal which is n times the current i to one which is m times the voltage e. The signal Δ is the difference between ni and me. It can be shown that

$$\frac{\Sigma^2 - \Delta^2}{4mn} = ei\cos\theta = \text{Power}, \qquad (2)$$

where θ is the phase angle between the current and voltage. The Σ and Δ signals are recorded on the intermediate-frequency systems in the usual manner. The measurement of total power is correct only for sinusoidal waves. For portable use, separate amplifiers and meters may be used in place of the recorders.

Figures 67 and 68 show the connections used in obtaining the Σ and Δ terms for unbalanced and balanced circuits.

In the actual circuit for an unbalanced load, a coil and pad replace the R_3 resistors in turn to obtain the Σ or Δ signal. The voltage component is obtained by short-circuiting R_2 and the current component, by disconnecting R_1.

In the balanced condition, the only new factor to be considered is the stray capacity between the two high potential terminals of the driving coil. This may be neglected for the usual load impedances. The impedances of the secondary windings will not affect the measurements.

It can also be shown that, if R_2 is center-tapped to ground, the meter will measure the power delivered

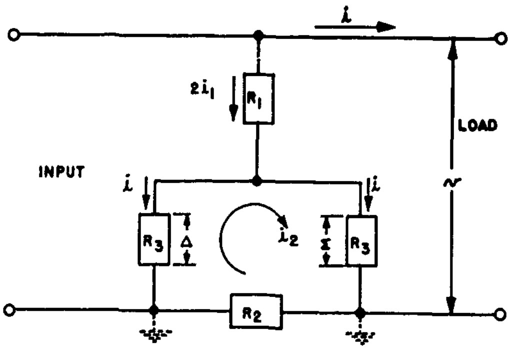

FIGURE 67. Recording wattmeter circuit for unbalanced load.

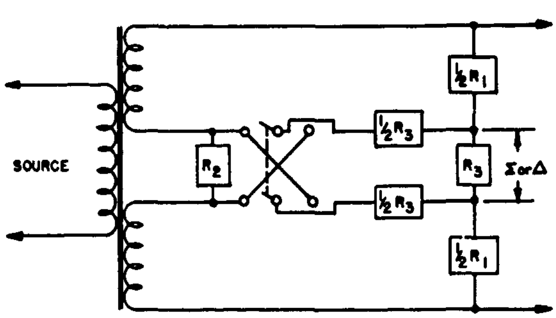

FIGURE 68. Recording wattmeter circuit for balanced load.

to both the load impedance and the impedance to ground. However, if no ground connection is made, the meter will read the load dissipation independent of the degree of unbalance.

The Σ or the Δ signal, depending upon the position of the reversing switch, will appear across R_3, which consists of a pad plus coil. Voltage and current components are obtained in the same manner as in the unbalanced case by short-circuiting R_2 and disconnecting R_1, respectively.

In the latest model of this wattmeter, the system can be changed from a balanced to an unbalanced condition by a switch on the front panel. In actual operations, four records are obtained on the chart paper, Σ, Δ, e, and i. Since the levels are recorded in db vs 10^{-16} watt, the subtraction of a proper constant from the recorded Σ level will give $\Sigma^2/4mn$ in db vs 1 watt. The same procedure and the constant are used to obtain Δ in the latter units. When these two readings are so converted, the difference between them will be the power delivered to the load. Similar procedures are used to convert the voltage signal to db vs 1 volt and the current signal to db vs 1 ampere.

It can be shown that the errors in the readings of the wattmeter are functions of the ratio me/ni and three ranges of impedance have been incorporated to keep these errors at a minimum. If the records of current and voltage differ by more than some 8 db in a particular region, their product will be in error as the above ratio indicates. An impedance range should be selected which brings the two signals closer together and thereby improves the accuracy of the power reading. These changes are readily made by means of a switch on the instrument.

The only element affecting the frequency characteristic of the wattmeter is the loss on the insertion of the coil replacing R_3. This will appear as a variation with frequency of the conversion constants but this effect over the range of 50 c to 150 kc is less than 0.4 db.

This wattmeter is used over a power range of 0.001 to 1,500 watts and an impedance range of 15 to 800 ohms. The accuracy is on the order of 1 to 4 per cent for phase angles up to 85 degrees. The accuracy beyond this angle has not been completely investigated experimentally.

Miscellaneous Equipment

General laboratory apparatus is available at all times for use with the circuits that are being developed and the construction that is in progress. This equipment includes decade condenser and resistance boxes, attenuators, storage batteries, and moderate stocks of fixed resistors, condensers, and inductors. Various switches and vacuum tubes are available in addition to transformers for power, signal frequencies, and variable voltage.

A modified Hallicrafters short-wave receiving set is used as a voltmeter and a harmonic analyzer for low-level signals at the higher frequencies (15 mc). It also provides an excellent means for detecting stray radiation.

6.3 DESCRIPTION OF ORLANDO TEST STATION

6.3.1 Site of Station

The Orlando station of USRL is located on Lake Gem Mary about 4 miles southeast from the center of Orlando, Florida. The lake is almost circular with a diameter of some 300 yards, which is ample for calibrations, yet it is not so large as to have high waves in windy weather. Typical of the lakes in this region, it is fed from subterranean sources and has no surface inlet or outlet streams. The depth of the lake varies with the amount of rainfall. This variation in lake level so seriously affects the calibration work that remedial measures are necessary. A pump is installed which draws water from an adjoining lake and automatically maintains the water level within ± 0.25 inches. The depths range from 15 to 18 feet under the test pier, which extends about 130 feet from shore, to 33 feet at the barge location in the center. These depths are satisfactory for testing purposes. The lake bottom consists of sandy loam, except for the central deep portion of soft mud. The acoustic absorption of the loam, as determined by tests, is high and increases with frequency. The reflected sound is 10 db below the incident at 20 kc, 15 db at 30 kc, and 20 db at 60 kc.

6.3.2 Facilities

The Orlando station provides facilities for the free field calibration of underwater sound devices in the frequency range from about 15 c to 150 kc. One object in setting up this station was to have a place where tests could be made when the water at Mountain Lakes is frozen. For this reason, outdoor facilities were of most importance, since the indoor facilities of

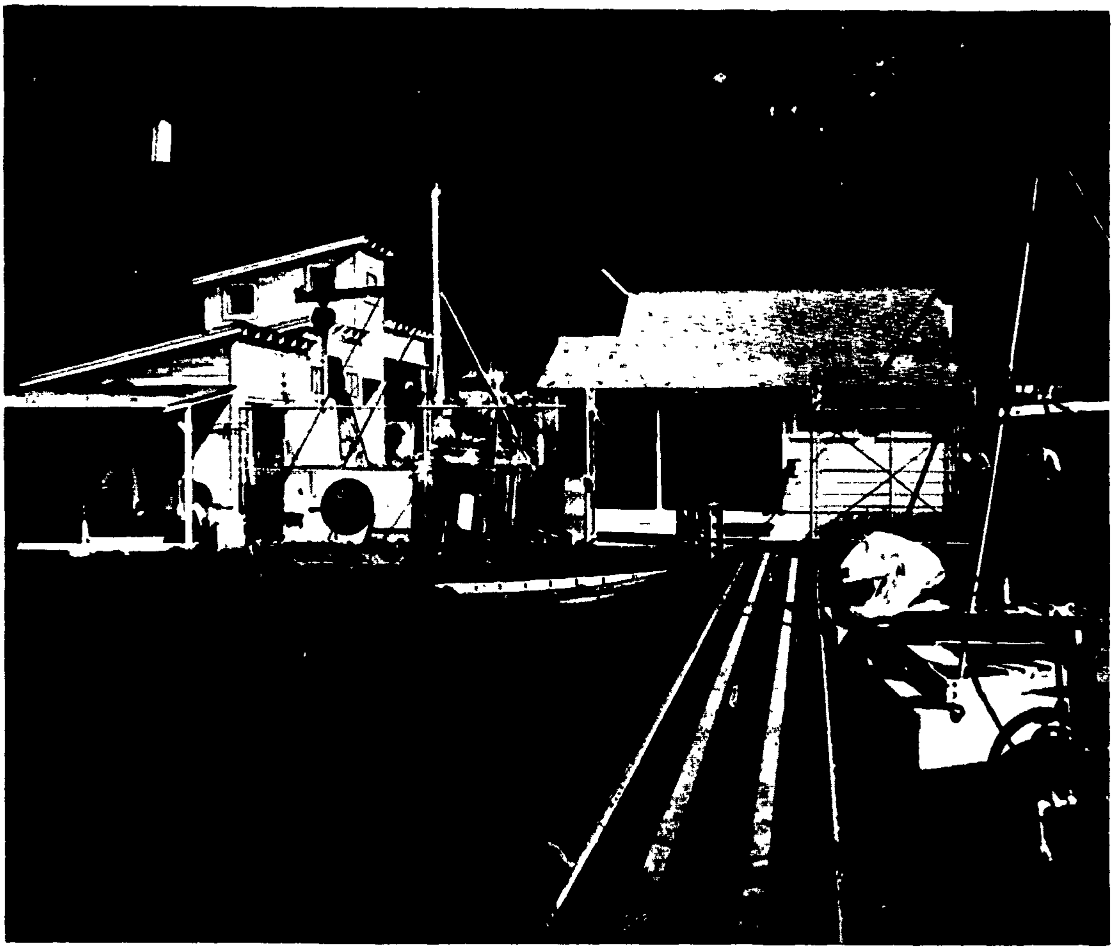

FIGURE 69. The Orlando test station as seen from the pier. Heavy equipment is loaded onto a mine car by means of the boom and chain hoist at the left. The rails on which the mine car runs are shown in the foreground.

Mountain Lakes are usable all year round. A fundamental requirement for the station was that the outdoor facilities in every essential respect be the equivalent of those at Mountain Lakes. This has been attained.

Orlando has two testing systems, one located on the pier, the other on a barge in the middle of the lake. The pier system is very similar to that at Mountain Lakes, but a number of modifications have been incorporated in the barge system to take full advantage of the deeper water available.

PIER SYSTEM

The test station proper is located on the eastern shore of the lake. As shown in Figure 69, a boom equipped with a chain hoist is provided at the loading platform. By these means, heavy equipment can be lifted out of a truck and loaded directly onto the mine car, which runs on a small spur track from the loading platform to the pier. At the point on the pier where the test pit starts, the equipment is transferred to a chain hoist running on an overhead rail to the outer end of the pier. Several chain hoists of different capacities are available. The pier is similar to the one at Mountain Lakes except for its length of 130 feet, which was required by the more gradual slope in order to reach a sufficient depth for testing. An awning that can be moved along the pier was installed to protect personnel and equipment from the heavy tropical rains.

Transmitting and receiving booths are located on the pier. The electrical equipment of each is equivalent to that in the corresponding booths at Mountain Lakes.

FIGURE 70. General view of the Orlando testing pier.

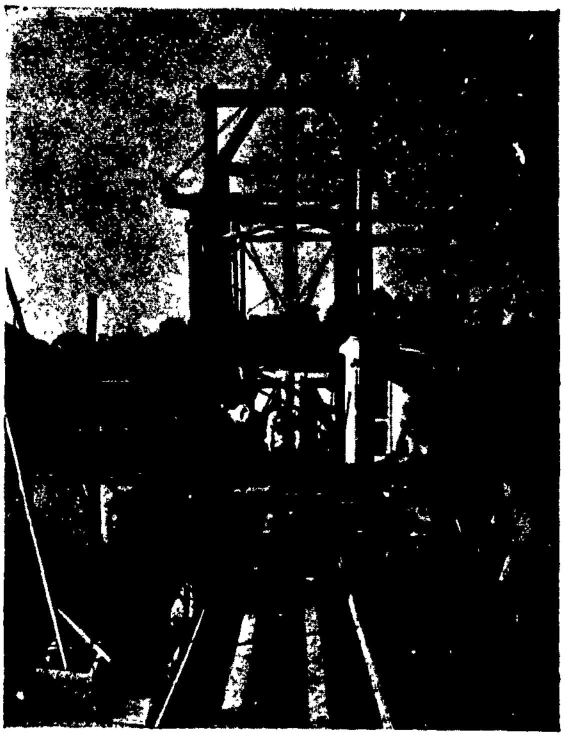

FIGURE 71. View of the Orlando pier from laboratory. The transmitting booth can be seen at the right. The receiving booth is at the far end.

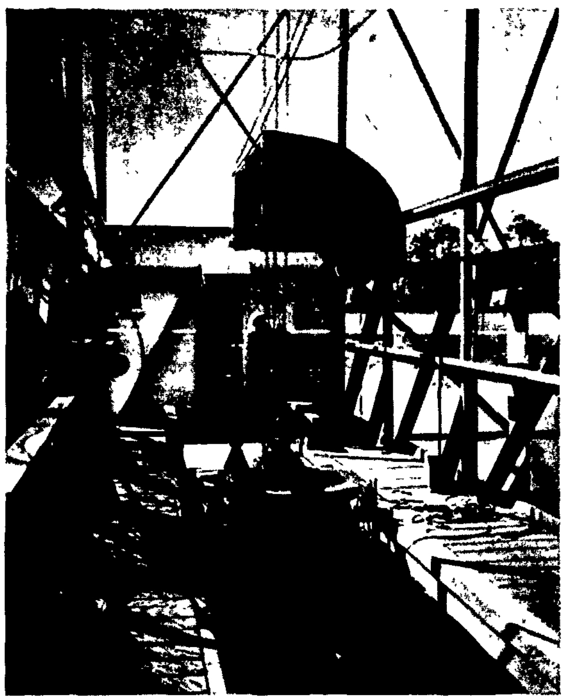

FIGURE 72. The receiving booth and the test basin at Orlando test station. A rotator designed for rotating a device around points other than the center of gravity can be seen at the far end of the basin.

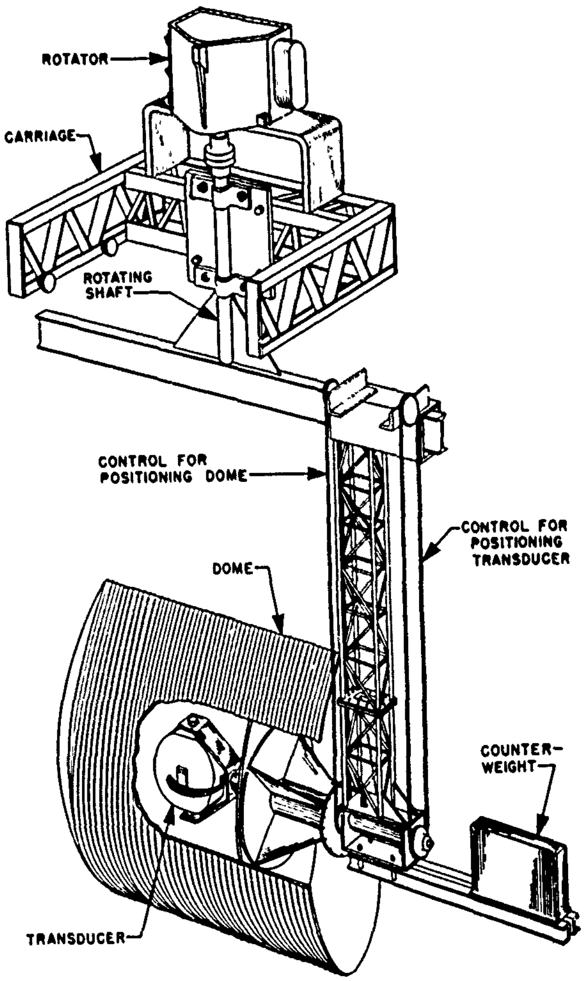

FIGURE 73. Sketch of offset rotator and synchro controlled rotator with attachment for taking directivity patterns of a transducer inside a dome.

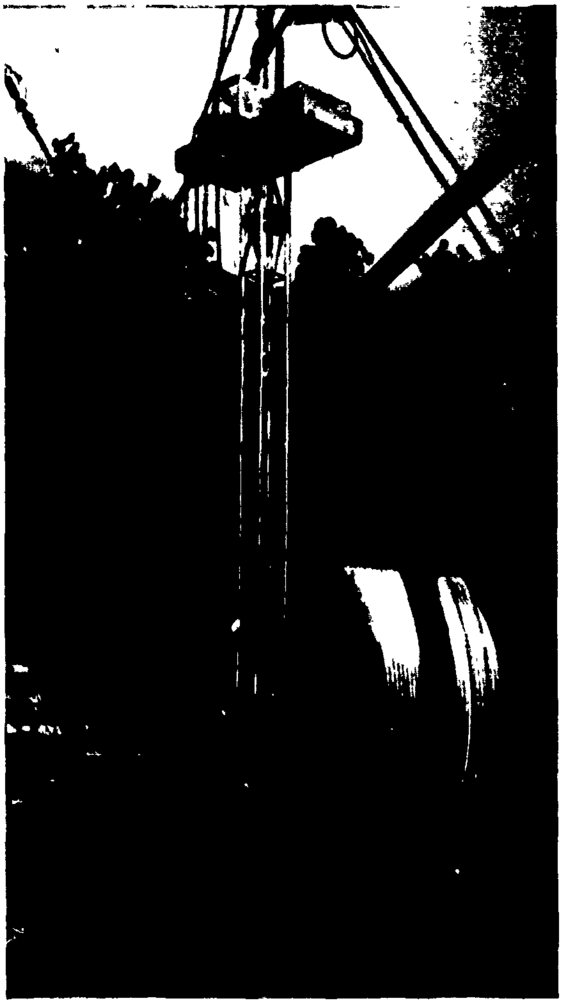

FIGURE 74. View of corrugated dome on special rigging for directivity measurements.

The types of carriages, suspension rods, and rotators with synchro control are identical with those at Mountain Lakes. The carriage shown at the far end of the test basin in Figure 72 is especially designed for use in the rotation of devices around points other than the center of gravity. This carriage and an offset rotator proved so useful that a synchro control was added. A further attachment was designed for taking vertical directivity patterns, such as that of an echo-sounding projector inside a dome. In this case, the dome is turned on its side, the projector mounted inside at any desired bearing relative to the nose, and the two are then rotated together. These features are shown in Figures 73 and 74.

The electric equipment for the pier station is housed inside the main building with the panels arranged in an arc facing the lake, as shown in Figure 75. The operator is stationed between these panels and a desk for recording test data, and a window above gives a view of the pier. The electric apparatus is similar to that at Mountain Lakes with the exception of the recorder and the high-power amplifier shown in Figure 78. Operation and circuit of the recorder have been described in Section 6.2.1. In this case, the drive by a double-armature motor is replaced by a magnetic clutch which makes contact between the rails of the pen carriage and either side of a continuously revolving disk. Coordination of the oscillator and the paper drive is obtained by driving both by one motor. The bay on the extreme left of

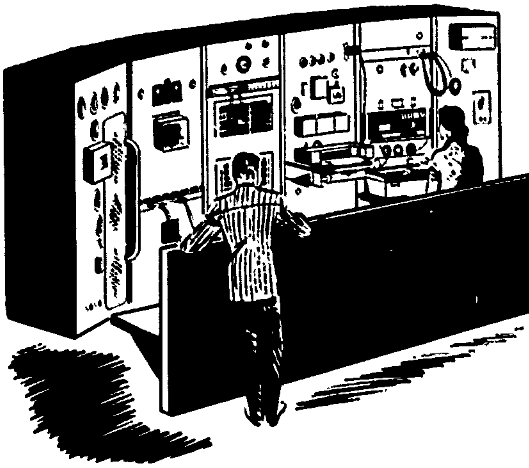

FIGURE 75. Arrangement of electrical equipment in the Orlando laboratory.

FIGURE 76. View of the Orlando barge. The barge is equipped with hoist arms at each end and a boom crane for handling equipment.

Figure 75 is part of the power amplifier system described above. It is capable of delivering 1,500 watts of electric power at frequencies from 2 to 100 kc. Facilities are available for the interconnection with other parts of the electric system and for measuring and accurately controlling the power levels. A wattmeter of the type developed by USRL is used with this unit and a motor generator set furnishes the 440-volt 3-phase power required.

Barge System

A general view of the barge is shown in Figure 76. The floor and frame are supported by 88 barrels, which are grouped uniformly under the floor and sectionalized so that individual units can be removed for repair or replacement without seriously interfering with the buoyancy of the barge. A pontoon is installed on the side where the house containing the electric equipment is located to provide the additional buoyancy necessitated by the uneven weight distribution. The barge is positioned by means of cables at the four corners attached to mushroom anchors imbedded in the lake bottom. Additional anchors of a screw type are connected by cables to winches which may be adjusted to level the barge and lower it in the water for greater stability.

Equipment is transported from shore in a flat-bottom boat of 1-ton capacity and raised onto the barge with a swivel crane.

The test basin is about 45 feet long and is fitted with steel rails which are spaced the same as at other USRL basins, to make possible the interchange of carriages between them. An overhead rail is used only in the center while wooden hoist arms, visible in Figure 76, are provided at each end of the test area. The hoists are lighter than a full length rail and are better adapted to handle the long rods that are used on the barge to take full advantage of the greater water depth. If the surface and bottom are total reflectors, the optimum testing depth is one-half the total depth but, if the bottom is absorptive, deeper testing would be advantageous. Actually, the tests are made at about one-half the water depth of 33 feet. Figure 77 shows a line hydrophone being mounted on a rod for testing at this depth. Hydrophones can be suspended either horizontally or vertically and operated with a synchro-controlled rotator similar to the one on the pier.

The building on the barge contains a complete electric testing system, including those facilities which are usually installed in the transmitting and receiving booths on the piers. The booths are not required here because of the short distance to the basin. The sending system is essentially the same as the one on the piers, but the detector is omitted from the receiving system so that the amplifier recorder is responsive to any signal within the frequency band of the system 200 c to 150 kc. This makes the system

more susceptible to noise and interference, but several fixed filters are available to restrict the receiving band when it is necessary to reduce the noise level.[e]

The linear recorder is of the same design as the one on the pier. The polar recorder is synchro-controlled from the rotator. The barge is also equipped for pulse testing with circuits which are identical with those at Mountain Lakes. The test-circuit cable from the pier is carried on the surface by drums spaced at various distances, while the power and communication cables rest on the lake bottom.

When tests are to be made over greater distances than the barge or pier areas permit, the distance is extended by a small triangular float which can be anchored anywhere in the lake and which is equipped with a simple hoist.

[e] This wide-band system was used because it was available at the time the barge was built, whereas the construction of a heterodyne and filter system would have entailed considerable delay. It may be noted that all the early testing systems of USRL were of the wide-band type.

FIGURE 77. Attaching a line hydrophone to special suspension rod on the Orlando barge.

6.4 RECOMMENDATIONS FOR IMPROVEMENTS OF THE USRL TEST STATIONS

The recommendations made in this section will deal mainly with improvements and additions that may be made to the existing electrical and mechanical components of the calibration systems. These improvements and additions are of an immediate practical nature and several are in the process of development. The general purpose is to increase the accuracy and ease with which the acoustic measurements are made and the resultant data converted into response, impedance, and other forms which characterize transducers. (See Chapter 4.)

General Improvements—Electrical

Under proper operating conditions the stability of the electric equipment now installed at USRL test stations is approximately 0.1 db. Signal generators are designed with very little drift in frequency. The gain of each individual component is as uniform as possible over the frequency range for which it is designed. This is done so that the relation of gain to

FIGURE 78. Part of the electrical system on the Orlando barge, including the linear recorder.

FIGURE 79. Small triangular float which can be anchored anywhere in the lake. Note the diver's helmet which is useful for inspecting underwater equipment.

frequency for each component may be neglected in the calculations. Although the present corrections lie within ±0.1 db, further improvement along these lines is possible.

General Improvements—Mechanical

Since the purpose of the mechanical systems in any acoustical calibration is to handle, hold, or orient the devices, any improvement which will reduce the time involved in rigging and measurement and still provide a minimum of interference in the sound field, is recommended. To minimize the number of systems required, each should be designed to handle as many different devices as possible.

Electromechanical Equalizer

Transducer calibrations would be greatly facilitated if only there were projectors which give a constant sound field over the whole frequency range, or hydrophones which had a uniform response for a constant field at all frequencies, or both. Either instrument would make possible the direct calibration of the other. Though no such ideal instruments are available, it is possible to approach the same result by proper control of the amplifier gain, or, what is more convenient, by control of the attenuation preceding a constant amplifier gain. The method is indicated in Figure 80.

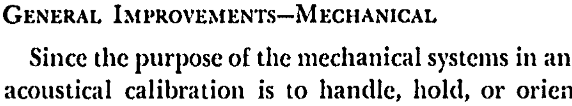

FIGURE 80. Schematic diagram of electromechanical equalizer.

Hydrophones are available which have been calibrated by reciprocity or other means. Using such an instrument with a fixed attenuation and amplifier gain, a recording is made as the projector sweeps over the range of frequencies. From the calibration curve of the hydrophone, a curve may be plotted which will give the strength of the sound field produced by the projector at each frequency. If a straight line is drawn parallel to the recorder axis and at some desired sound level, the difference between it and the projector curve will be the number of decibels by which the actual field differs from a constant one. If some device connected to the attenuator can be made to follow the curve and thus vary the output level so that it will be proportional to the deviation of the curve from a straight line, the output of the amplifier will be at a constant level. In other words, the record would be that of a flat hydrophone in a constant sound field. If now the coupling loss of an unknown hydrophone is determined and the corrections for this loss added to the original curve, the resulting control curve will cause the attenuator to correct for both the variations in the projector output and the coupling loss. If this hydrophone is placed in the field of the projector and its output is fed through the attenuator with its gain controlled by the curve, the hydrophone signal will have added, at every frequency, the number of db necessary to make its output what it would have been if the projector output had been constant. In other words, the record is the response of the unknown hydrophone in a constant sound field. The same technique will give a correction curve for a hydrophone and allow the direct calibration of a projector. Calibration by this method eliminates the time and errors involved in the point by point computations required at present. The data are in such a form that the calibration can be reproduced directly by photographing the recorded chart.

Such a system is under consideration by USRL,

and a tentative design is partially completed. The curve tracer mechanism is based on a light-beam and photoelectric cell null-balancing scheme.

Transient Wave Analyzer

In the study of wave forms, the use of the Henrici analyzer for the measurement and analysis of transients has proved both time-consuming and expensive. Therefore, USRL later developed an instrument which not only may be constructed from inexpensive and easily available parts but also speeds up the process of analysis. (See Figure 81.) This transparent cylinder is rotated by a motor at about 1,800 rpm running between a light source on the inside and a narrow slit outside. The light passing through the slit impinges on a photoelectric cell of the vacuum photomultiplier type. The associated tube circuit for amplification is shown at the right of the figure and the power supply at the left. The usual recording system for any steady-state signal such as system 2 is used beyond this point.

Figure 81. Optical signal generator of apparatus for transient analysis.

In operation, an oscillogram of the transient is reproduced as an opaque stencil and attached to the surface of the cylinder. It is then rotated between the light source and the photoelectric cell producing an electric signal corresponding to the transient which is repeated some thirty times each second. The envelope of the amplitudes of the Fourier components of this signal is proportional to the spectral distribution of energy in the transient. This envelope may be obtained directly as a function of the frequency by using system 2 with the 300-c band which will average several adjacent harmonics. The record obtained will be independent of the lowest Fourier frequency as long as it is small compared to 300 c, since changing the frequency and amplitude of the linear sweep corresponds to changing the scale factor in a Henrici analysis. (See references 58 and 79.) Calculations made from this record are identical with those from the Henrici analyzer.

After a careful adjustment to eliminate distortion, several transient sounds from Navy devices were analyzed by this method. The results were carefully checked to determine their validity. The accuracy of the reproduction was tested by viewing it on the CRO, and the broad-band rms level of the original transient was compared with the one delivered by this apparatus. As an additional check, a square wave was analyzed. Since the Fourier analysis of this wave is mathematically known, the analysis of the instrument could be readily compared with the theoretical values. Good agreement was found to exist between the two.

There are minor improvements which could be made, but the instrument as it stands is workable and has adequate precision. The speed and facility in the analysis of pulse signals have been very much improved. Obviously, the method may be applied to electrical pulses from any source.

If no analyzer such as system 2 is available, the amplitudes of the Fourier components may be determined with a commercial electric harmonic analyzer. The phases of the components, however, cannot be determined by either method.

Acoustic Phase Measurements

For a more complete characterization of transducers, an instrument is desired which measures the phase between the acoustic signal and the electric signal. This would be of advantage, particularly in the analysis of transient wave forms.

Phase bridges are available[66,76] that measure the relative phase between two electric signals. This limits measurements in acoustic tests to the difference in phase between the current into a projector and the voltage generated by the hydrophone. However, the reciprocity relation of a transducer indicates that the phase shift between the current and the generated pressure when acting as a projector, minus the phase shift between the applied pressure and the open-circuit voltage when acting as a hydrophone, is either 180 or 0 degrees for a magnetostrictive or a piezoelec-

tric instrument. This assumption or preferably an exact knowledge of the phase constant plus the phase measurements on the three possible combinations of a projector, hydrophone, and reversible transducer, would be sufficient to obtain the phase shift between the incident pressure of the hydrophone and its generated voltage. The time delay in the acoustic medium would have to be taken into account, but once such a standard had been calibrated, an unknown could be determined by comparison. Measurements of this nature have not been made to date by the Underwater Sound Reference Laboratories.

Improved Variable Band-Pass Filter

An instrument which proves of value in both the analysis of noise and the characterization of transducers is a continuously variable width band-pass filter centered at any given frequency. The filter of this nature described previously requires too much auxiliary equipment and is awkward to use. A simpler and self-contained one is most desirable. For example, it is often important to describe a hydrophone's performance in terms of the response to a given band width of noise centered at a specific frequency. Such a filter could be readily used in conjunction with a noise source to provide the necessary signal.

Improved Pulse Recorder

One of the inconveniences of the present pulse recorder is the fact that its sensitivity and performance are not independent of the pulse length and rate of repetition. A recorder to overcome these difficulties is very desirable.

Recording Impedance Bridge

A continuous-recording impedance bridge would be of great value to any laboratory concerned with electric and acoustic measurements. The recording wattmeter already described can be used for impedance measurements and with high accuracy if combined with an insertion-type phase bridge mentioned above. Both the ratio of voltage to current and the phase could be determined by the amount of attenuation called for by the two null-balancing circuits. Recorders of the same general type as those used in the electric systems of USRL laboratories would provide a continuous record of the attenuation inserted and hence a continuous record of the phase and magnitude of the impedance

Absorbing Materials

A perfect absorbing material would provide almost ideal testing conditions when operating in small space. It is felt that there is a possibility of producing better absorbing materials or combinations of materials than have been developed up to the present time. Any improvement along these lines would be of aid not only in calibration techniques but also in the design and application of acoustic devices.

Directivity Index Measurement

The directivity index of a projector is necessary for the computation of its efficiency. In general, this index can be obtained only by computation from the directivity patterns and even then with limited accuracy. Because of the large amount of time required for these computations, the University of California Division of War Research has built a system for making direct measurements of the directivity index. It consists in rigging the projector so that it can be rotated and the acoustic output integrated over the surface of a surrounding sphere by means of the watt-hour meter. The directivity index is the ratio in db of this integrated power to the area of the sphere times the acoustic power per unit area on the acoustic axis.

Chapter 7

COMPUTATION FROM TEST DATA

By *Eginhard Dietze* and *L. Pauline Leighton*

The method of computing the calibration of an instrument from the test data is described in this chapter. Reference should be made to Chapter 6, which outlines the procedure for taking test data, and to Chapter 4, which gives the theoretical background for these computations.

For a numerical example, the calibration of a transducer is given, since such a unit can be operated as both a receiving and a sending device, affording the opportunity of illustrating both types of computation.

7.1 RECEIVING RESPONSE

To test the receiving response over a wide frequency range, several sets of tests with a number of projectors may have to be made. However, since the computation is the same at all frequencies, only one set of data is discussed here, and the numerical computation is limited to one frequency, 25 kc.

It is assumed that calibrated standards are available so that the comparison method may be used. This is the usual test procedure as discussed in Chapter 6. The computation of the calibration of the standards themselves by reciprocity is discussed in Section 7.4.

Usually several standards are used in one test to provide a mutual check on their performance. In this discussion, however, attention is confined to a single standard, a type 3A hydrophone. The calibration of the 3A standard, serial No. 89, used in this particular illustration is shown in Figure 1.

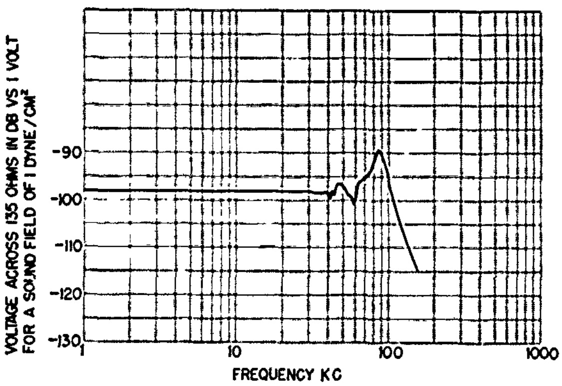

Figure 1. Calibration of 3A89 crystal hydrophone.

The data furnished by the test station are illustrated by the receiving response charts, Figures 2 and 3, and by Figure 4, which shows a log sheet applicable to these tests. Figure 2 shows a receiving chart for the 3A89 hydrophone and Figure 3 a receiving chart for the transducer under test. The conditions of the tests applicable to these two receiving charts are stated on the log sheet, from which can be obtained:

1. The testing distance between the source and the hydrophone.
2. The available power that was used for the projector.
3. The receiving amplifier gain that was used in the tests.
4. A reference to the circuit sketch for this test.

With these data on hand, the calibration can proceed. The first item to be checked is whether or not the same testing distance was employed for the test unit as for the hydrophone standard. If not, the readings must be corrected to the same testing distance by means of the formula given in Chapter 4,

$$C = 20 \log \frac{d}{d_0}, \tag{1}$$

where d and d_0 are the testing distances for the test unit and for the hydrophone standard respectively.

It will be recalled that the receiving response usually is expressed in terms of the generated voltage of a hydrophone. One exception to this rule is in the calibration of the 3A hydrophones, in which the response is expressed in terms of the voltage across 135 ohms.

The receiving charts give the level (in db vs 10^{-16} watt) impressed on the recorder. A number of corrections have to be applied to obtain the generated voltage of the hydrophone from the chart readings. Corrections must be made for (1) the receiving amplifier gain, and (2) the coupling loss. By the latter is meant the loss (or gain) in the voltage applied to the input to the receiving amplifier as compared to the generated voltage of the hydrophone. Since the loss in the line

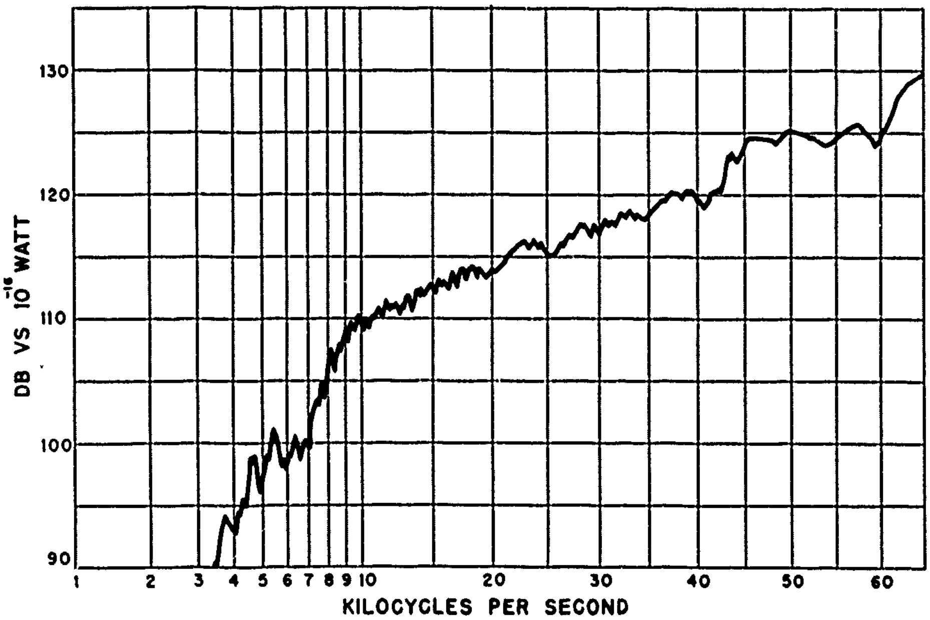

FIGURE 2. Receiving response chart, 3A89 hydrophone vs AX70 projector. Reference run No. 1 on log sheet (Figure 4).

from the pier to the receiving amplifier is included in the calibration of the system, the voltage at the line terminals may be substituted for the voltage at the input to the receiving amplifier.

Referring to the example, the log sheet in Figure 4 contains a reference to the circuits used for the standard and the transducer under test. These circuits are reproduced in Figures 5 and 6. It may be seen that the transducer was connected through a balanced coupling amplifier to the 135-ohm receiving line. To evaluate the coupling loss of this amplifier, two measurements were made, as shown in Figure 7. First, a volt-

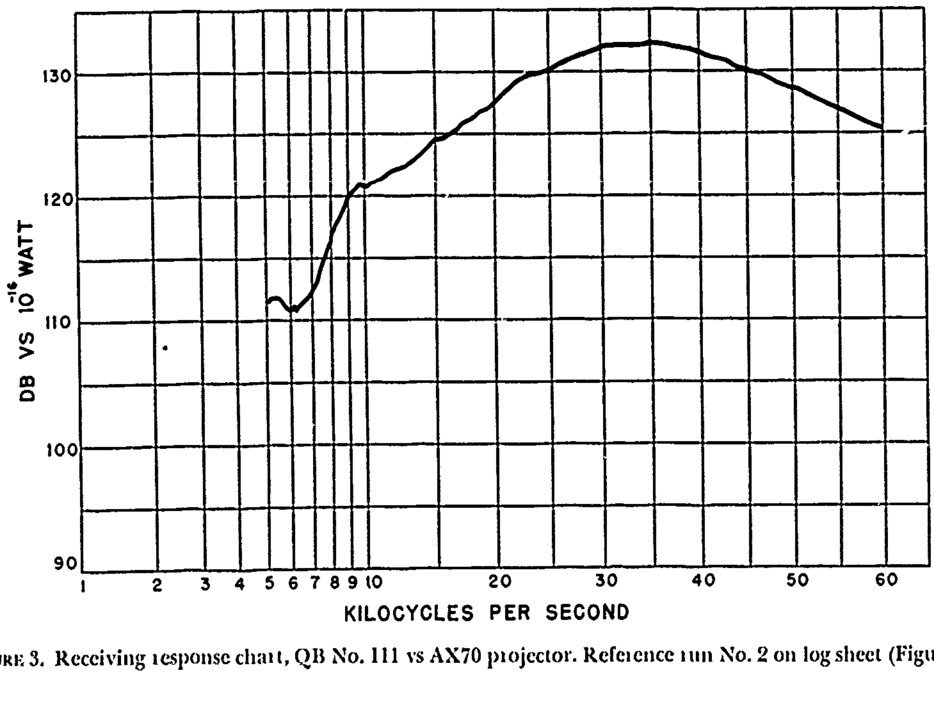

FIGURE 3. Receiving response chart, QB No. 111 vs AX70 projector. Reference run No. 2 on log sheet (Figure 4).

LOG

Orlando TEST STATION 1 SYSTEM; 1 PIER

PROJECT NO. 000 DATE 12-26-44 COPIES TO STATION FILE AND N.Y OFFICE 2 SHEET NO. H 1

INDEX: Run No.	Type*	Color	Location	Ref. Cct.	Time	WATER TEMP: Deg C	Depth CM	TRANSMITTING: Proj. Type-No.	φ/θ	Pier Pos. CM	Depth CM	Avail. Power: Zo	Level	FREQUENCY-KC: Single, Range, or Mid-Band	Pulse: Tr	Rec.	Length-MS: Tr	Rec	Dly MS	Rate PPS	RATES: Sweep	Paper IPM	Rec RPM	RECEIVING: Hydro Type-No.	φ/θ	Depth CM	Horiz Dist CM	Sys Gain db
1	R	BL	A	I	9:30	20	280	AX70	0°	100	268	600	150	2.5-100							m	6		3A 89	+90	268	250	50
2	R	BL	B	II	9:40	"	"	AX70	"	"	"	"	"	5-90							m	6		QB#111	0/6	"	"	54
3X	CO	G	C	III	9:50	—	—	coup. amp. out						0-110							f	18		—	—	—	—	20
4X	CI	R	C	IV	9:50	—	—	coup. amp. in						"							f	18		—	—	—	—	20
5	R	BL	D	V	10:30		280	QB#111	0/6	100	268	135	160	10-60							m	6		3A89	+90°	268	250	4
6X	R	R	E	VI	10:40	receiving system				—	—	—	—	0-150							f	18		—	—	—	—	0
7X	R	G	E	VII	10:45	transmitting system				—	—	135	-150	0-150							f	18		—	—	—	—	0

LOG(10-41) *R RESPONSE; CI-CPLG IN; CO-CPLG OUT; D-PATTERN; IN INHN'T NOISE; NA NOISE AGTAT'N; I PROJ CUR; E PROJ VLT ...

SHEET NO. H

FIGURE 4. Sample log sheet covering calibration of QB No. 111 transducer.

age was applied to the receiving line from a very low impedance, 0.034 ohm, as shown in (a) of Figure 7; this same voltage was then applied to the receiving amplifier through the coupling amplifier, as shown in (b) of Figure 7. The two recorder traces are shown in Figure 8. The log sheet shows that both measurements were made with the same receiving amplifier gain. Thus, the difference between the two traces gives the coupling gain or loss. It will be seen that this loss is 6.2 db at 25 kc.

The generated voltage of the test instrument relative to the voltage of the 3A hydrophone across 135 ohms can now be computed as follows:

Difference in receiving chart readings . . . . . (From Figures 2 and 3)	+15.2 db
Coupling loss for test hydrophone . . . . . . (From Figure 8)	+6.2 db
Difference in receiving amplifier gain . . . . . (From Figure 4)	−4.0 db
Difference in available power to projector . . . (From Figure 4)	0 db
Difference in testing distance . . . . (From Figure 4)	0 db
	+17.4 db

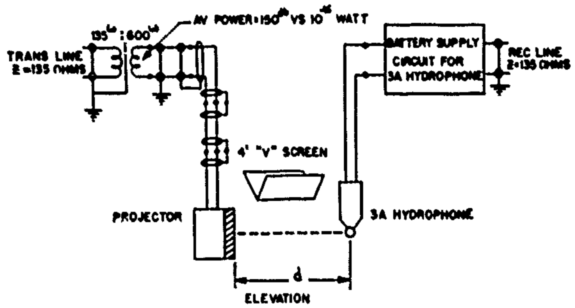

FIGURE 5. Circuit used in obtaining reference receiving response chart, 3A89 hydrophone.

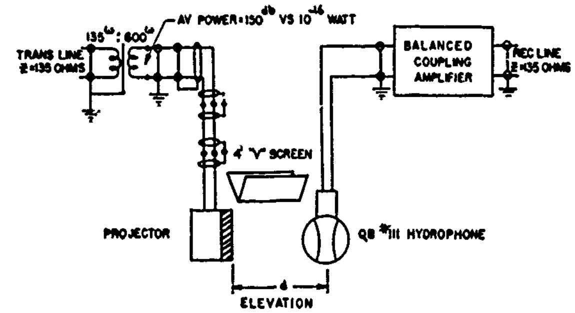

FIGURE 6. Circuit used in obtaining receiving response chart, QB No. 111 transducer.

With the calibration of the hydrophone standard (Figure 1) known, the receiving response of the test instrument may be obtained as follows:

The response of the standard, according to Figure 1, is −98.2 db vs 1 volt for a sound field of 1 dyne per sq cm at 25 kc. The response of the test instrument, in accordance with the above computation, is 17.4 db

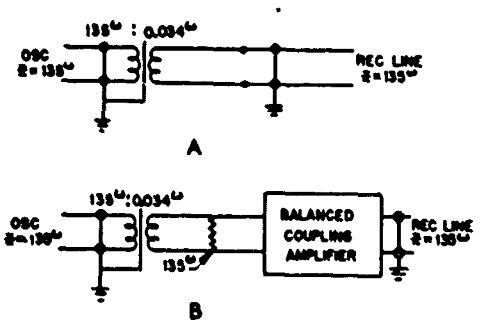

FIGURE 7. Circuits used in obtaining coupling loss for 3A89 hydrophone. (A) For measuring input voltage (see run No. 4, Figure 4). (B) For measuring output voltage (see run No. 3, Figure 4).

higher. Thus the result obtained is that the projector at 25 kc has a receiving response of −80.8 db vs 1 volt per dyne per sq cm.

The preceding computation, which was carried through at one frequency only, is repeated at selected frequencies throughout the entire frequency range. From these data, a response characteristic is plotted as shown in Figure 9.

In these particular tests a 3A hydrophone, which is a pressure-actuated device, was employed as a standard. If the hydrophone standard is of the pressure-gradient type, such as the 1A or 2A hydrophone, it generates a gain in the voltage, especially at low frequencies, due to the curvature of the wave front. Figure 13 in Chapter 5 shows the magnitude of the spherical wave correction for different testing distances, plotted against frequency. The indicated response of the test hydrophone, because of this gain in the hydrophone standard (if the latter is of the pressure-gradient type), is lower than it would be if the tests were made in a plane-wave sound field. To refer to plane-wave conditions, therefore, the relative response must be correspondingly increased.

7.2 THRESHOLD AND IMPEDANCE

After the receiving response characteristic has been determined, it is possible to compute the threshold characteristic. Equation (18) in Chapter 4 gives an expression for the threshold pressure. It can be seen that this pressure depends on the resistance of the hydrophone as well as on its response. It is therefore necessary to compute this resistance. The chart in Figure 10 shows readings for the projector taken at the test station by means of the 5A impedance bridge. This bridge gives the admittance in terms of parallel resistance and capacity values. Since the bridge can measure directly only impedances below 1,000 ohms, it is necessary to shunt the unknown impedance whenever it exceeds that value. The bridge shunt resistance used is given in Figure 10 as R_0 and the bridge resistance reading as R_b.

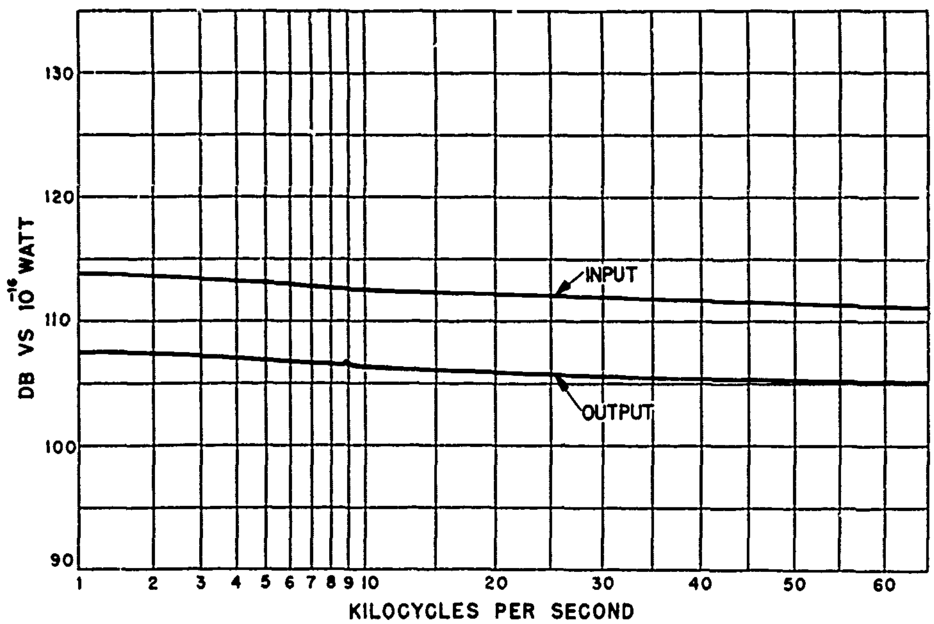

FIGURE 8. Chart of coupling loss for 3A89 hydrophone.

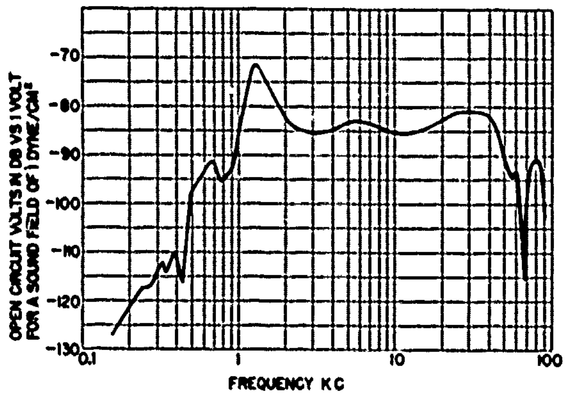

FIGURE 9. Receiving response of QB No. 111 transducer.

The first step in computing the impedance from the values on the chart is to compute the unknown parallel resistance, which is

$$R = \frac{R_0 R_b}{R_0 - R_b}. \tag{2}$$

IMPEDANCE

Orlando Test Station

Project No. 149 Date 12-29-44 Copies 2 Copy to E.D. Sheet No. E 1

Device: Desig. QB # 111 Type ADP crystal projector (parallel siding)

Measuring conditions:

Location of device: 5' beneath surface - water temp - 62°F

Grounding effects water ground on case of projector

Bridge and Auxiliaries:* D.C. & Leakage Resistance:

Osc. 17B

Bridge 5A

*Bal. ✓ Unbal. ___

Detector 31ATMS

lead to lead		ohms	lead to lead		ohms
L+	L-	1.6	L-	R+	>30 meg.
R+	R-	1.5	Shield		
L+	R- R+	>30 meg	Shield to Case		>5 meg.

I = Current through Bridge

R_0 = Measured value of Shunting Resistance

R_b = Value of Bridge Resistance balanced against Resistance of Unknown.

Note: Check in first column under R_b indicates unknown has been shunted by R_0.

-Cp = Value of Bridge Capacitance balanced against Capacitance of Unknown.

+Cp = Value of Bridge Capacitance to Resonate with Inductance of Unknown.

f KC	I	R_0	R_b ✓	R_b Value	Cp
1		1006 3	✓	967 2	+.11036
5		10069	✓	9603	-.037201
10		1007.3	✓	937.3	-.039226
20		1007.5	✓	822.2	-.041163
22		10077	✓	781.5	-.041525
24		1007.7	✓	736 8	-.041870
25	•	1007.7	✓	781 5	-.041525
26		1007 8	✓	694.0	-.042150
28		10079	✓	655.8	-.042430
30		10079	✓	618 0	-.042650
32		1008 0	✓	591 3	-.042869
40		1008 2	✓	560 6	-.045700
50		1008.5		1057.7	-.050554
60		1008 8		594.3	-.060930
70		1009 2		2997	-.078982
80		10092		64.2	-.115465

FIGURE 10. Sample data sheet giving 5A impedance bridge readings obtained in measuring the impedance of the QB No. 111 transducer.

From the computed shunt resistance R and the shunt capacity C (given in microfarads on the chart), the equivalent series resistance r and series reactance x are then computed by means of the formulas

$$r = \frac{R}{1 + (\omega RC)^2} \tag{3}$$

and

$$x = -\frac{\omega R^2 C}{1 + (\omega RC)^2}. \tag{4}$$

This process, carried through numerically at 25 kc, gives

$$R = \frac{1,007.7 \times 781.5}{226.2} = 3,450 \text{ ohms,}$$

$$r = \frac{3,450}{1 + 394} = 8.7 \text{ ohms,}$$

and

$$x = -\frac{68,200}{1 + 394} = -173 \text{ ohms.}$$

This computation is repeated at other frequencies, and an impedance characteristic is plotted for the instrument, as shown in Figure 11. The threshold then is computed by means of equation (18) in Chapter 4. This computation at 25 kc is as follows:

$$\begin{aligned} T &= 10 \log r - 194.9 - R_R \\ &= 10 \log (8.7) - 194.9 + 80.8 \\ &= -104.7 \text{ db vs 1 dyne per sq cm.} \end{aligned}$$

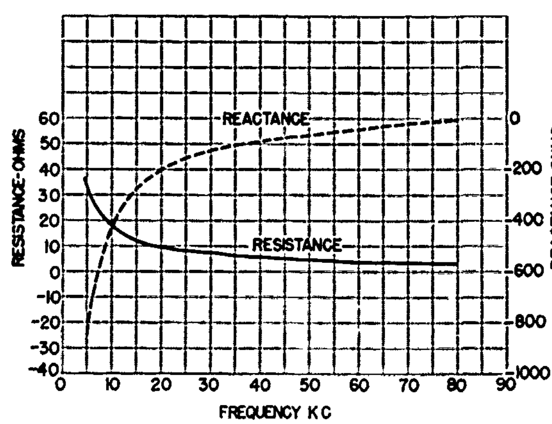

FIGURE 11. Impedance characteristic of QB No. 111 transducer.

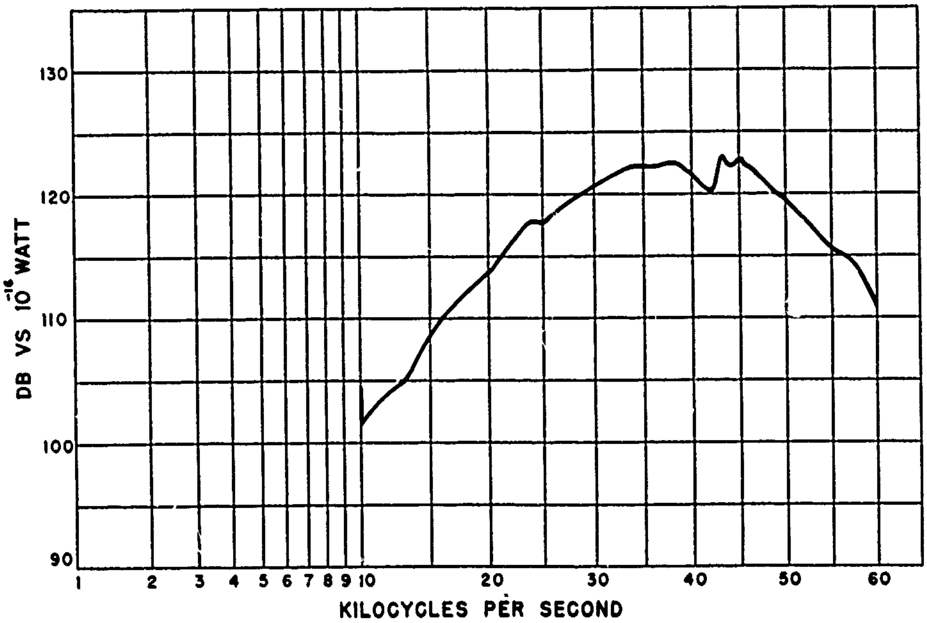

FIGURE 12. Transmitting chart, QB No. 111 transducer vs 3A89 hydrophone (see run No. 5, Figure 4).

7.3 TRANSMITTING RESPONSE

Transmitting tests are similar to the receiving tests described above. Figure 12 shows the transmitting chart of the projector, using for the sound receiver the same 3A hydrophone standard as in the receiving tests. Reference should be made again to the log sheet (Figure 4) for the details of this run.

This log sheet shows that the available power supplied to the projector was 160 db vs 10^{-16} watt (i.e., 1 available watt) from 135 ohms. The log sheet also refers to the test circuit used in the transmitting tests. This circuit is reproduced in Figure 13. The receiving amplifier gain given on the log sheet is 4 db, and the testing distance is given as 250 cm.

From this information it is possible to compute the transmitting response. This computation is carried through numerically at 25 kc as follows:

Chart reading, vs 10^{-16} watt in 135-ohm circuit	+118 db
Correction for receiving amplifier gain	−4 db
Correction for testing distance: 20 log 2.5/1	+8 db
Correction for available power referred to 1 available watt	0 db
Level at hydrophone terminals, vs 10^{-16} watt in 135-ohm circuit	+122 db

In order to obtain the pressure in the sound field, it is now necessary to refer to the calibration of the 3A hydrophone shown in Figure 1. This calibration is in terms of db vs 1 volt. The computed level at the hydrophone must, therefore, be changed into these terms. This correction is as follows:

When the power dissipated in a 135-ohm resistance is 10^{-16} watt, the voltage e across that resistance is given by the relation

$$\frac{e^2}{135} = 10^{-16}$$

so that

$$e^2 = 135 \times 10^{-16}.$$

On a decibel basis relative to 1 volt, this gives

$$20 \log e = 10 \log(135) - 160$$

$$= -138.7 \text{ db vs 1 volt.}$$

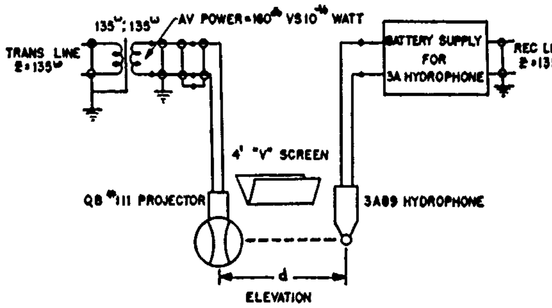

FIGURE 13. Circuit used in obtaining transmitting chart, QB No. 111 transducer.

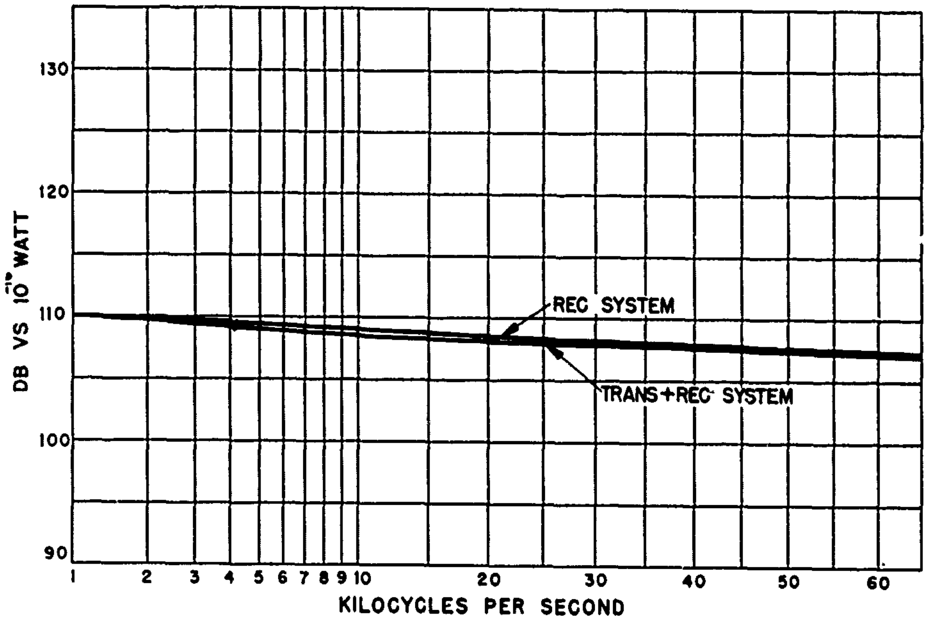

FIGURE 14. Response characteristics of transmitting and receiving systems during calibrations.

The voltage delivered by the 3A hydrophone consequently is

$$122.0 - 138.7 = -16.7 \text{ db vs 1 volt.}$$

The calibration chart (Figure 1) shows that, if the sound pressure is 1 dyne per sq cm, the hydrophone delivers -98.2 db vs 1 volt. For the voltage to be -16.7 db, the sound pressure must have been 81.5 db above 1 dyne per sq cm. Thus, the transmitting response of the projector at 25 kc is found to be $+81.5$ db vs 1 dyne per sq cm.

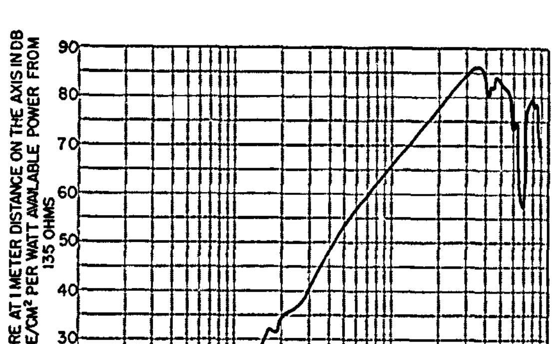

FIGURE 15. Transmitting response of QB No. 111 transducer.

The electrical system is usually adjusted at one frequency, and the sensitivity may vary somewhat with frequency. When this is the case, a compensating correction must be made in the transmitting response. Figure 14 shows response characteristics of the transmitting and receiving systems used in the present tests. At 25 kc this correction amounts to about 0.5 db. The transmitting response must therefore be increased by this amount, i.e., the transmitting response is actually 82.0 db vs 1 dyne per sq cm.

This computation when carried out over the frequency range gives the transmitting response characteristic of the projector, shown in Figure 15.

After the transmitting response has been obtained, the projector efficiency is computed. This requires a knowledge of the directivity at the frequency at which the computation is made. Figure 16 shows a directivity pattern of the projector taken at 25 kc. Chapter 4 contains descriptions of graphical charts which facilitate the computation of the directivity index from the measured directivity pattern. Since the side lobes of this particular pattern are low, it is possible to base the computation on the relation between the beam width and the directivity index for a circular piston (see Figure 7 in Chapter 4). The beam width in this case is 19.8 degrees, giving a directivity index of -24.2 db by the chart.

Equation (8) in Chapter 4 gives the expression for

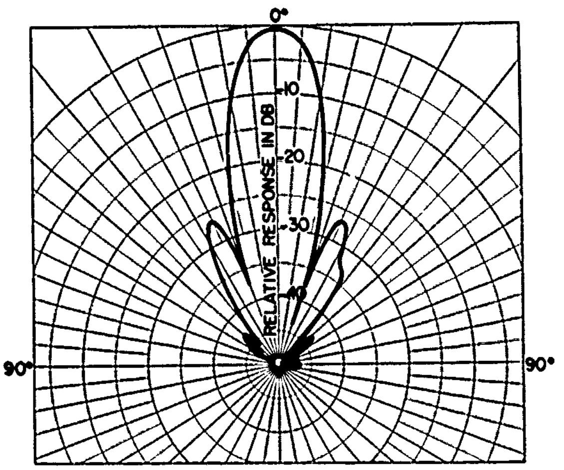

FIGURE 16. Measured directivity pattern of QB No. 111 transducer at 25 kc. Directivity index computed from this pattern = −24.1 db.

the projector efficiency. The only factor still unknown in this expression is $10 \log P_I/P_A$. This expression can be evaluated from the impedance of the projector and the source impedance (see equation (2) in Chapter 4):

$$10 \log \frac{P_I}{P_A} = 10 \log \left[\frac{4rr_g}{(r_g + r)^2 + x^2}\right]$$

$$= 10 \log \left[\frac{4 \times 8.7 \times 135}{143.7^2 + 150^2}\right]$$

$$= -9.6 \text{ db.}$$

The efficiency can now be stated

$$E_p = +82.0 - 24.2 + 9.6 - 70.9 = -3.5 \text{ db vs ideal.}$$

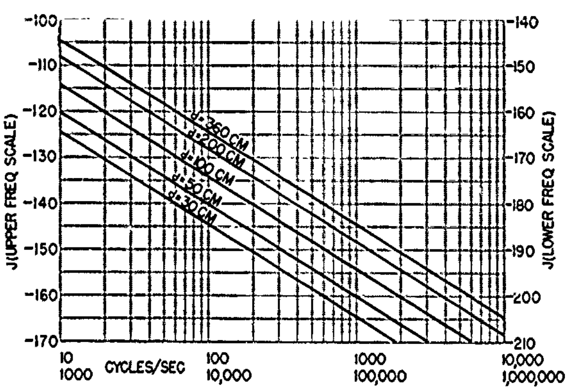

FIGURE 17. Reciprocity parameter for water.

$$J = 20 \log \left[\frac{2d\lambda}{\rho c} \times 10^{-7}\right].$$

7.4 RECIPROCITY CALIBRATION OF STANDARDS

The comparison method of calibrating acoustic devices depends on the availability of standards whose calibration is accurately known. The next problem, then, is to calibrate these standards. As discussed in Chapter 5, the best method for obtaining an absolute calibration is by means of the reciprocity principle, which permits a determination of the response from purely electrical measurements. The reciprocity calibration requires considerably more work and is more critical than a relative calibration. Therefore its use should be confined to the fundamental calibration of hydrophone standards, with which all other instruments can then be compared.

The relation by means of which the reciprocity calibration of a hydrophone can be obtained is given in Chapter 5. In decibel form this equation is

$$R_r = \tfrac{1}{2}[J + 20 \log e_h + 20 \log e_h' - 20 \log e_t - 20 \log i] \quad (5)$$

where $J = 20 \log (2d\lambda/\rho c \times 10^{-7})$. The term J is the *reciprocity constant*. This parameter for water for a number of testing distances is shown in Figure 17. The term e_h is the open-circuit voltage generated by the device in a given sound field, e_t is the open-circuit voltage generated by an auxiliary transducer in the same sound field, and e_h' is the open-circuit voltage of the device in the sound field produced by the auxiliary transducer when a current i flows through it.

The data usually are furnished by the test station in terms of level in db vs 10^{-16} watt rather than voltage. The matter of translating levels into db vs 1 volt is discussed in Section 7.3. Since most of the circuits used at the test stations have an impedance of 135 ohms, it is sufficient here to consider that case, in which the correction is −138.7 db. The above equation can now be written in terms of levels:

$$R_r = \tfrac{1}{2}[J + L_h + L_h' - L_t - 20 \log i - 138.7]. \quad (6)$$

Usually the same transducer is used for the calibration of a number of hydrophones. Then the following quantities, which are independent of the particular hydrophone being calibrated, can be computed, and the result used as a constant k in the other reciprocity computations:

$$k = J - L_t - 20 \log i - 138.7. \quad (7)$$

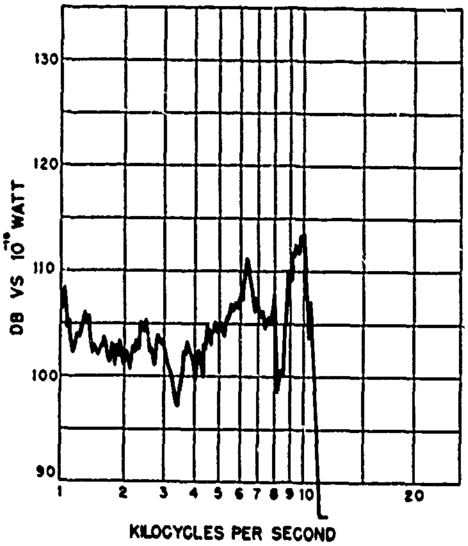

FIGURE 18. Receiving chart. 1K13 projector acting as a hydrophone vs 1K25 projector acting as a sound source.

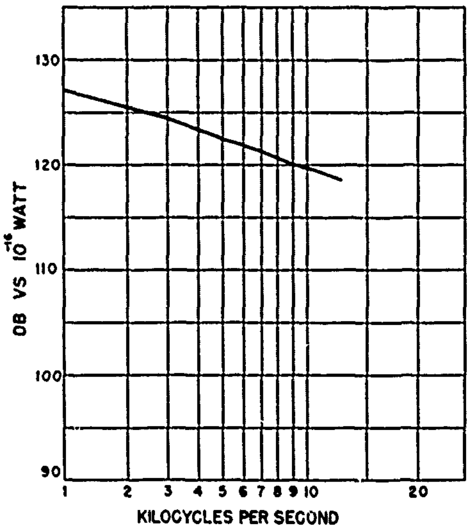

FIGURE 19. Chart of current in the 1K25 projector acting as a sound source.

In the following, the computation of the absolute reciprocity calibration of a 3A hydrophone is carried out at 1,000 c from test data which have been obtained at the station. In these tests, the 1K13 projector was used as the auxiliary reversible transducer and the 1K25 as the other sound source.

Figure 18 shows a receiving chart for the 1K13 projector, taken with the 1K25 projector acting as the sound source.

The pertinent test conditions are recorded as usual on a log sheet. The following information at 1,000 c is taken from that sheet:

Transmitting conditions for 1K25 projector
  Source impedance = 4 ohms
  Available power = 150 db vs 10^{-16} watt
Testing distance = 45.7 cm
Receiving conditions for 1K13 projector
  Coupling loss = 0.6 db (as shown by chart readings—see Section 7.1)
  Receiving circuit = 135 ohms
  Receiving amplifier gain = 30 db

Figure 19 shows a chart of the current in the 1K25 projector when 150 db vs 10^{-16} watt available power is supplied to it from a 4-ohm source. In order to convert the current chart reading into db vs 1 ampere, it is necessary to use the current-measuring circuit calibration. In this particular case, this calibration is as follows: The level indicated by the recorder when 1 ampere flows in the current-measuring circuit is 112 db vs 10^{-16} watt. Thus 112 db must be subtracted from the chart readings.

In addition to the chart in Figure 17 giving the value of the reciprocity constant J, the charts in Figures 18 and 19 are sufficient for the computation of the constant k.

It is desirable in this computation to reduce all values to a standard test condition which will be used in the subsequent tests on the hydrophones whose absolute calibrations are to be obtained. This test condition will be based on (1) an available power level for the projector of 160 db vs 10^{-16} watt, and (2) a testing distance of 30.5 cm.

The value for the reciprocity constant J can be read from the chart in Figure 17. At 1,000 c for a testing distance of 30.5 cm this figure is −164.3 db.

The level received in the 135-ohm circuit is obtained as follows:

Receiving chart reading (Figure 19)	+107.6 db vs 10^{-16} watt
Correction for receiving amplifier gain	−30.0
Correction for coupling loss	+0.6
Level received in the 135-ohm circuit	78.2 db vs 10^{-16} watt

This level must be reduced to standard conditions by two corrections:

1. The testing distance was 45.7 cm. If the measure-

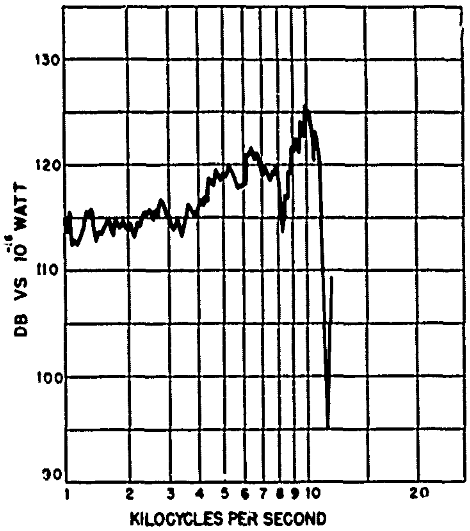

FIGURE 20. Receiving chart. 3A74 hydrophone vs 1K13 projector as the sound source.

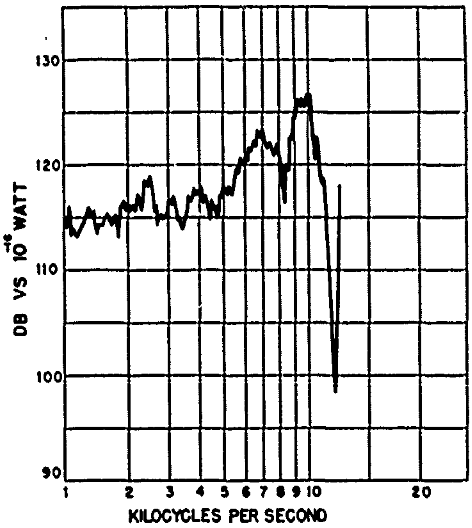

FIGURE 21. Receiving chart. 3A74 hydrophone vs 1K25 projector as the sound source.

ments had been made at 30.5 cm, the level would have been increased by

$$\frac{20 \log 45.7}{30.5} = +3.5 \text{ db.}$$

2. The available power into the projector was 150 db vs 10^{-16} watt. With 160 db available power, the level would be increased by +10.0 db.

Making these two corrections gives

$$L_t = 91.7 \text{ db vs } 10^{-16} \text{ watt.}$$

The current chart reading in Figure 19 at 1,000 c is 127 db vs 10^{-16} watt. From this reading must be subtracted the receiving amplifier gain, in this case 40 db, and the correction factor which converts the reading into db vs 1 ampere, 112 db, as stated above. In addition, the reading must be increased by 10 db, on the basis that the standard test condition uses an available power level of 160 db rather than 150 db. Thus,

$$20 \log i = (127 - 40 - 112 + 10)$$

$$= -15 \text{ db vs 1 ampere.}$$

Thus the constant k is obtained:

$$k = -164.3 - 91.7 + 15 - 138.7 = -379.7 \text{ db.}$$

The reciprocity calibration of any desired hydrophone can now be obtained from two receiving level charts, L_h and L_h', taken of that instrument with the 1K13 projector and with the 1K25 projector. These data must be for the test condition for which k was computed, that is, a testing distance of 30.5 cm, and an available power into the projector of 160 db vs 10^{-16} watt, or else corrections must be made to reduce the data to these conditions.

Figure 20 shows a receiving chart for the 3A74 hydrophone taken with the 1K13 projector as the source. Figure 21 shows a receiving chart for the same instrument taken with the 1K25 projector as the source. Both charts were taken at a testing distance of 30.5 cm, with an available power of 160 db applied to the projector. Consequently, no corrections for testing distance or available power need be made. A correction, however, must be made for the receiving amplifier gain, which was 20 db in both cases. Since the hydrophone in both tests was across a 600-ohm line, no coupling correction is required if the receiving response is desired in terms of the output voltage from the preamplifier across 600 ohms.

Reference to the chart in Figure 20 shows the level

reading at 1,000 c to be 114.8 db vs 10^{-16} watt. Correcting this for the receiving gain (20 db) gives

$$L_h = 94.8 \text{ db vs } 10^{-16} \text{ watt.}$$

Similarly, from the chart in Figure 21,

$$L_h' = 115 - 20 = 95 \text{ db vs } 10^{-16} \text{ watt.}$$

Thus, the absolute calibration of the 3A hydrophone can be computed at 1,000 c:

$$R_r = \tfrac{1}{2}(-379.7 + 94.8 + 95)$$

$$= -95.0 \text{ db vs 1 volt across 600 ohms}$$

for a sound field of 1 dyne per sq cm.

Chapter 8

PRODUCTION TESTING OF SONAR TRANSDUCERS

By *Erwin F. Shrader*

8.1 GENERAL CONSIDERATIONS

PRODUCTION testing may be distinguished from type testing. Before a design is adopted, very careful calibrations must be made on a number of samples or pre-production models. The models are then taken out to sea for performance tests. Often several modifications are made in the original design before it is acceptable. When a satisfactory type is finally evolved, the manufacturer proceeds with the production of the device. Specifications are set up to make the product as much like the samples as possible. To insure this, tests must be made on each unit; thus production testing involves calibration, albeit in simplified form.

A production testing program serves two purposes: (1) It insures that each product meets certain specifications, and (2) it permits quality control, that is, a running check on the quality of the manufactured products which notes and corrects any deviations from the accepted standard. Without regard to the detail of the nature of the test or of the device under consideration, certain basic requirements must be met in order to have a successful production test. The procedure must involve a relatively simple technique not requiring highly trained personnel. The time required for each test must be short. The test should not be affected by conditions beyond the operator's control, such as phenome· a of noise interference, water temperature, etc.

Production testing of a sonar transducer falls into two parts: (1) tests of physical strength, watertightness, and polarity of electrical elements, and (2) acoustic measurements of directivity, response, and impedance. This chapter deals only with tests falling in the second category.

In connection with acoustic production tests, lakes and rivers are, in general, eliminated from consideration as testing sites on the following counts: (1) They are, as a rule, separated from the factory; (2) the conditions there may not be sufficiently well controlled for routine testing; (3) they may be subject to noise from water traffic. An indoor tank in the factory offers the best chance of circumventing these difficulties while still meeting the requirements of simplicity, speed, and sufficient accuracy. It is true that, in a confined body of water, proximity effects and reflections are present and will affect the measurements. On the other hand, there are various methods of eliminating the effects of these reflections and of correcting for proximity effects. (See Chapter 5 for complete discussion.) These methods will be considered here with particular application to the problem of acoustic production testing procedure.

8.2 PRODUCTION TEST MEASUREMENTS

The measurement of the acoustic properties of a sonar transducer has been discussed in Chapters 4, 5, and 6. For a complete description of a sonar transducer, it is necessary to know the receiving or transmitting response as a function of frequency, the impedance as a function of the frequency,[a] and the directivity patterns at several frequencies in one or more planes, depending on the symmetry of the device. Since the test requirements for each of these measurements are by no means identical, it is necessary to discuss the requirements for each measurement separately and to evolve a test procedure which satisfies the maximum demand of each test. It should be kept in mind, however, that each type of transducer will be a special problem and that, in many cases, certain measurements may be considerably simplified and sometimes even eliminated.

8.2.1 Response Measurements

For a production test of response, an absolute measurement is not necessary. The response of the transducer can be compared directly with that of a secondary standard, which may be a transducer of the same type meeting manufacturing specifications. The calibration of the secondary standard should be obtained from a complete free-field calibration. A relative

[a] Impedance measurements have been included in this group, since they depend on the acoustic terminating impedance of the transducer.

measurement of response in a production test performed in a comparatively small tank may involve a smaller testing distance than is required to render negligible the various proximity effects. Such a test can nevertheless be satisfactory, provided there is a definite correlation between comparison measurements on the standard and on the units under test at large and at small distances.[55]

Unless proper precautions are taken, response measurements made in a tank are not precise because of the interference between the direct and reflected waves. If the testing distances required because of proximity effects are not too large, it may be practicable to use a fairly small tank with walls having from 15- to 20-db absorption.[b] Such absorption will reduce the intensity of the reflected waves sufficiently to reduce the error in the axis response to ± 1 db (under steady-state conditions). If the units to be measured are directional, and if directional standards are used, the sources of the more bothersome reflections may be treated with the recently developed "bubble" layer, which provides 5- to 10-db absorption and probably renders negligible the overall remaining reflection interference. (See Chapter 6.)

In addition to, or in place of, the use of absorbing walls, electrical methods for eliminating the effects of reflections may be employed. These methods involve the use of noise or frequency warble, or of pulses. The relative advantages of these methods are discussed in Chapter 5. Their usefulness depends on the nature of the response of the transducer being tested, since each method entails a loss of resolving power in the curves of continuous-wave response versus frequency. For a unit with fairly uniform response (Q small), all of these methods are quite satisfactory, since little resolving power (RP) is required ($RP \cong Q$). For a highly resonant transducer, the use of all these methods with a tank of given size is limited by resolving power consideration. The resolving power will have to exceed Q, and this implies a minimum allowable path difference ΔL between direct and reflected waves, greater than cQ/f,[c] for example, greater than 3 meters for $f = 25$ kc and $Q = 50$. Regarding the relative merits of continuous-wave noise or warble versus pulses, the latter may be considered superior, since with their use reflections can be eliminated completely from the measurements, while with the former the reflections are averaged in and yield a time-independent, but not always known, correction.

8.2.2 Impedance Measurements

The measured electrical impedance of a transducer depends on the terminating acoustic impedance. (See Chapters 3, 4, and 5.) This fact deserves consideration because the presence of reflected waves incident on the face of the transducer constitutes a change in the terminating acoustic impedance and so will affect any electrical impedance measurement. If the impedance measurements are made in a tank with absorbing walls, the reflections may be sufficiently small to allow the measurements to be made in a conventional way with an impedance bridge.

On the other hand, when the reflections are appreciable, their effect can be eliminated by pulsing. The pulse length is presumably determined by the same criterion as in the directivity pattern and response measurements (see Section 8.2.3). For pulse measurements, a wattmeter with a time constant small compared to the length of the pulse may be used.[d] In this case the impedance is obtained from voltage, current, and power.

8.2.3 Directivity Pattern Measurement

The measurement of directivity patterns imposes the most severe test requirements. This is chiefly due to the fact that measurements of intensity 40 or 50 db below the response on the axis must be made in competition with reflections of the main beam. Even with the best of the available absorbing materials, it is impossible to prevent some reflections from interfering with the measurement of the directivity pattern of a moderately directional transducer. Noise and frequency warble are not suitable for directivity measurements because they average in an interfering reflection of unknown magnitude with the direct signal. The error introduced thereby may be considerable for certain directions, as when a direct signal received

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[b] An absorbing tank approximately 3 ft long by $1\frac{1}{2}$ ft wide by $2\frac{1}{2}$ ft deep has been built by the Bell Telephone Laboratories.[35]

[c] Here c is the velocity of sound, f is the frequency, Q is defined precisely in Chapters 4 and 5. A derivation and discussion of this equation is given in Chapter 5.

[d] The recording wattmeter described in Chapter 6 can be used in conjunction with a pulse recording system. Indeed, this system has the additional advantage of being able to measure impedance at high power levels without unduly heating the transducer.

off the axis of maximum response is averaged with a reflection incident on the projector axis.

Pulse measurement, therefore, is the only feasible method for obtaining directivity patterns, and even this method has its limitations. As noted above in the discussion of response, and as described in detail in Chapter 5, the pulse method discriminates against reflections by measuring the direct signal before the reflection arrives. The time elapsing between the arrival of the direct and reflected signals is a function of the size and shape of the testing tank. The practical limits to the maximum allowable size of such a tank restrict, in turn, the maximum length of time during which the pulse measurement may be made. The maximum elapsed time needed for a significant measurement of the response depends on the transient response of the transducer to a suddenly applied sinusoidal signal, that is, the pulse. For transducers whose frequency response characteristic is fairly uniform, the response reaches its steady-state value in a short time, i.e., a few cycles, and very short pulses and consequently small testing distances may be used. For resonant transducers, the time needed for the response to reach its steady-state value is long. In this case, the directivity patterns can be measured only by using long pulses, and correspondingly long testing distances are required.

The quantitative criterion for the minimum allowable path difference ΔL between the direct and any reflected wave, a quantity which must be just larger than the pulse length, has been given above as $\Delta L > cQ/f$. A theoretical analysis indicates that a much shorter pulse length, and so a much shorter minimum path difference, may be used in taking the directivity pattern at the resonance frequency of a highly resonant transducer. The criterion for ΔL in this case is $\Delta L \cong$ transducer diameter. However, this theoretical analysis assumes that the transducer diaphragm moves rigidly, a condition not generally obtained in practice.[e]

The directivity pattern as measured should be a close approximation to the directivity pattern that would be obtained at large distances. In order to meet this requirement, the test distance should be such that proximity effects are small, that is, the spherical wave correction should be less than a few db. It is questionable whether patterns taken at a shorter test distance can be compared with corresponding patterns taken on a secondary standard. There is undoubtedly some correlation between the directivity patterns of the standard and of the test unit at large and at small distances, but the relation is in general a very complex one.

8.3 TANK DESIGN CONSIDERATIONS

Since the pulse method seems best for directivity measurements, the specifications for a tank suitable for that method will be discussed. Assume that the test distance and pulse length are chosen on the basis of the foregoing discussion. The absorption of the tank walls is of little moment for pulsing. Frequently, however, steady-state measurements of response and impedance are to be made in the same tank. For these, the absorption of the walls should be made as great as practicable. Tank walls made of wood or concrete offer several db of absorption. If the concrete tank is set in the ground, the damp earth provides additional acoustic loss on reflection. A steel tank is to be avoided, if at all possible, because of the high reflection coefficient. A bubble layer may be applied to the walls to increase the absorption if it proves necessary.

The maximum repetition rate of the pulses used depends on the reverberation time of the tank. If a high repetition rate is desired for ease of measurement, some wall absorption should be supplied.[f]

While many tank shapes are possible, the simplest to build is a rectangular one as deep as it is wide. It can be shown that, for a given testing distance and reflection path length, the minimum size is obtained when the line joining the projector and hydrophone is parallel to the long dimension of the tank. This assumes that the reflection path lengths from the sides, top, and bottom of the tank are equal to those from the ends. For this arrangement (Figure 1) the length of the tank is given by $l = d + \Delta L$, where l is the length of tank, d is the test distance, and ΔL is the path difference required.

The width and depth necessary are equal and are given by the relation $w = \sqrt{2d\Delta L + \Delta L^2}$.

It may be possible to reduce the width of the tank somewhat by the use of completely reflecting baffles

[e] See reference 55 for report on investigation of the effect of pulse length on pattern for a representative resonant transducer ($Q \cong 50$) operating at the resonance frequency.

[f] For example, in a tank with an average dimension of 15 ft and a wall absorption of 3 db per reflection, about 23 milliseconds are needed for the intensity of a reflection to fall 45 db.

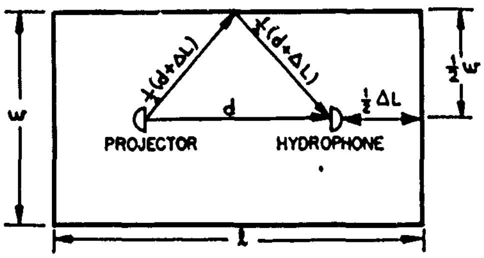


FIGURE 1. Optimum test geometry in a simple rectangular tank without baffles designed for a given test distance and reflection path length.

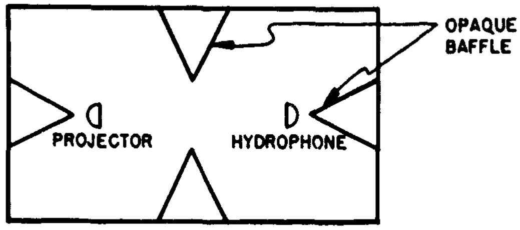


FIGURE 2. Arrangement of baffles in a rectangular tank for the interception of principal reflections.

placed in such a way as to intercept the reflection from the side of the tank. One possible arrangement of baffles is shown in Figure 2. This procedure cannot be used to eliminate reflections, but it will increase the effective path length between them.

8.4 CHOICE OF SECOND TRANSDUCER

The choice of the second transducer to be used in the acoustic production test measurement depends in general on the instrument under test. For receiving response measurements the second transducer must be a sound source, and vice versa. Its response should be fairly uniform over the frequency range being investigated, so that it responds rapidly to acoustic and electric transients; that is, the time constant of the second transducer should be small if it is to be used in pulse testing. Also, if its response is uniform, slight inaccuracies in frequency will not cause appreciable errors. The transducer should be fairly stable and show only small changes in response with temperature.

For continuous-wave noise or warble measurements, the transducer should be directional. This will help to discriminate against reflections coming from directions other than that of maximum sensitivity. However, since at a given frequency greater directivity can be obtained only by increasing the size of the transducer, there will be a certain maximum directivity beyond which it will be impossible to go. Furthermore, the proximity effects increase with transducer size.

The NDRC 6B standard projector will be a suitable transducer for most of the cases encountered. Any other transducer with similar properties will also be suitable.

8.5 NATURE OF PRODUCTION TEST

The degree of refinement of a production test depends on the information desired. A calibration test system such as that described in Chapter 6 is capable of giving a permanent record of any and all characteristics of a transducer. If the response of a transducer at only a few discrete frequencies is needed, the test system may be a tank, oscillator, standard transducer, and a suitable a-c voltmeter. The response in this case is given simply as a meter reading recorded by the operator. Likewise, if only a few features of a directivity pattern are required, no complicated polar pulse recording system is needed. A simple way of measuring relative magnitudes of pulses is to use an attenuator in the circuit to keep the magnitude of the observed pulses constant on a cathode-ray tube screen. The settings of the attenuator give the relative magnitudes of the pulses. In this way, a directivity pattern may be constructed from point by point observations. While this procedure is laborious, the number of tests to be made may not justify a more complicated system.

The pulse method is recommended for determining the directivity patterns of large echo-ranging projectors. The pulse length used depends on the response characteristic, in the manner described above. The tank must be large enough to satisfy proximity effect and reflection path length requirements.

For measuring the response of small transducers, testing distances may be short, and some sort of tank with absorbing walls may be practical. While the pulse technique is still applicable, continuous-wave or noise and warble methods may be simpler and yield results within the accuracy desired.

The absorbent tank described above will also be adequate for continuous-wave measurements of the electric impedance of most devices.

Chapter 9

ACOUSTIC EQUIPMENT ASSOCIATED WITH UNDERWATER SOUND DEVICES: DOMES AND BAFFLES

By *Henry Primakoff* and *Joseph B. Keller*

The Underwater Sound Reference Laboratories has calibrated acoustic equipment auxiliary to electroacoustic transducers. Among the most important auxiliary equipment tested have been streamlined domes and baffles.

9.1 DOMES[48,52]

In general, a streamlined dome is necessary for an echo-ranging or listening device to minimize noise by reducing the turbulence and cavitation about its active face arising from its passage through the water. The alternative possibility of streamlining the device itself has not been widely adopted.

The dome should be properly streamlined, that is, it should be of such a size and shape that turbulence and cavitation noises are eliminated, or at least do not set in until high speeds of the vessels are reached. Further, the dome structure should have sufficient mechanical strength to resist the hydrodynamic pressure and drag forces on it and should be constructed from a noncorrosive, sea-resistant material. Finally, the dome should be acoustically transparent, causing as little disturbance as possible in the magnitude and directivity of the response of the enclosed acoustic device.

To be acoustically transparent, the dome must fulfill three requirements.

First, the dome must introduce only a small transmission loss. By such a loss is meant the reduction in the magnitude of the response of the transducer caused by placing it in the dome; usually this is measured along the transducer axis. Thus, for an echo-ranging projector a 3-db one-way transmission loss means a 50 per cent decrease in the pressure amplitude of any echo received by reflection from a target.

Second, the dome must introduce no large side lobes in the directivity pattern of the enclosed transducer. Such lobes may arise as a result of internal specular reflections from the dome and cause false bearings to be taken in echo ranging or directional listening. For example, if a listening or echo-ranging device on an antisubmarine vessel is trained in the direction of the transducer axis as indicated in Figure 1, and an enemy submarine is present in the direction of the internal specular reflection, a relatively strong signal will be received. The vessel may then assume that the signal is being received on the main lobe, and head into the indicated bearing. Actually, in this case, the vessel should head in the direction of the specular reflection.

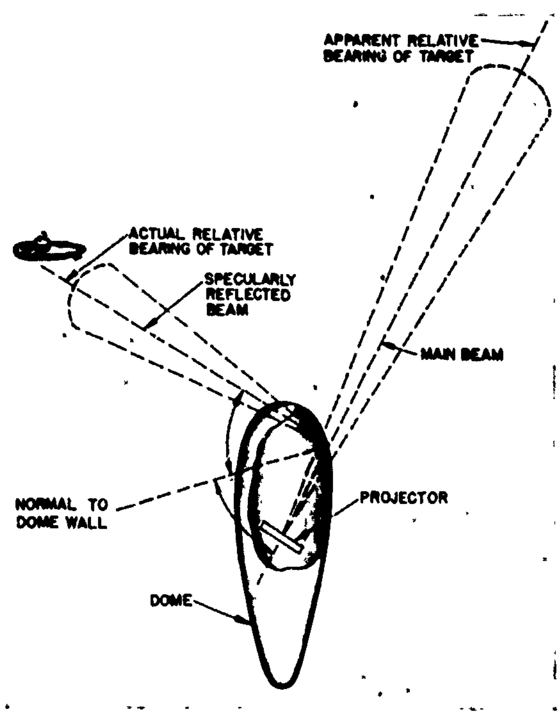


FIGURE 1. Specular reflection in domes.

In addition to introducing one relatively strong internal specular reflection, domes also distort the transducer directivity patterns by giving rise to various second order effects such as multiple reflections. Multiple reflections introduce additional side lobes

in the pattern, increasing such effects as the rear response. However, if the domes are well designed acoustically, these additional side lobes are usually over 20 db down with respect to the main lobe. For this reason it is generally desirable to distribute the sonic energy contained in a single internal specular reflection among many directions unless the specularly reflected beam can be intercepted and further subdivided or absorbed.[48,52] Furthermore, the enclosure of a transducer in a dome should not appreciably alter the width of the main lobe or increase the magnitude of the side lobes already present in the transducer patterns. (These two effects are quite small in well-designed domes.)

Third, the enclosure of a transducer in a dome should not appreciably alter the radiation impedance of the transducer. (Impedance change is usually very small in well-designed domes.)

Acoustical disturbances introduced by domes, such as specular reflections and transmission losses, are interrelated. In general, a dome which introduces small transmission losses also causes small specular reflections. (A quantitative relation between the two is given later.) Moreover, because the change in the radiation impedance of the transducer is small, its total power output is unaffected by enclosing it within a dome; also, true absorption of sound within the dome wall is negligible for metal domes. As a result, the energy which is removed by the dome wall from the impinging transducer beam and which constitutes the transmission loss is redistributed in directions other than the original direction of incidence; in particular, the major portion of this energy is concentrated into the direction of specular reflection.[a] This redistribution has the effect of increasing the value of the directivity factor δ. (The directivity factor is related to the directivity index by the expression $\Delta \equiv 10 \log \delta$. See Chapters 3 and 4.) Thus, for an echo-ranging projector:[64]

$$P = \frac{p_1{}^2 \delta}{\rho_0 c_0} = \frac{p_1{}'^2 \delta'}{\rho_0 c_0} \tag{1}$$

where

P = acoustic power output of echo-ranging projector,

p_1 = axis pressure output of bare projector at 1 meter,

p_1' = axis pressure output of dome-enclosed projector at 1 meter,

δ = directivity factor of bare projector,

δ' = directivity factor of dome-enclosed projector,

ρ_0 = density of water, and

c_0 = velocity of sound in water.

Therefore, the one-way transmission loss TL introduced by the dome, defined by

$$TL = 20 \log \frac{p_1}{p_1'}, \tag{2}$$

is, from equations (1) and (2)

$$TL = 20 \log \frac{\delta'}{\delta}. \tag{3}$$

Thus, the expression TL is a measure of the change in the transducer directivity index introduced by the dome.

Expressions may now be obtained theoretically for the magnitudes of both the transmission loss and the specular reflection induced by a dome of given material, wall thickness, and dimensions, on an enclosed transducer of given frequency, directivity, and position within the dome.[48] These expressions are found by determining the effect of dome enclosure on the sound field of a transducer; they agree generally with experimental tests on domes performed by USRL.[b] The expression for the transmission loss (and so by equation (3) for the dome-induced change in directivity index) is:

$$TL \cong 10 \log \left[1 + \left(\frac{\rho_1 d k_0}{2\rho_0} \right)^2 \right], \tag{4}$$

where

ρ_1 = density of dome wall material,

ρ_0 = density of water,

d = thickness of dome wall,

$k_0 = \frac{2\pi}{\lambda_0} = \frac{2\pi f}{c_0}$,

λ_0, c_0 = wave length and sound velocity in water,

and

f = frequency.

[a] Thus, the magnitude of the additional side lobes introduced by the dome into the directivity pattern, for example, the additional rear response, increases as the transmission loss increases.

[b] See STR Division 6, Volume 11.

It is important to note that the transmission loss is determined solely by the thickness and density of the dome wall and by the frequency of the transducer and is independent of the transducer directivity, of its position within the dome, and of the dimensions of the latter.[c] Thus in particular, with d, ρ_1, and f fixed, the dome may be made of any size and shape, for example, elongated for streamlining purposes, without the transmission loss being affected. Regarding numerical values, equation (4) predicts, for example, that a 50-mil steel dome at a frequency of 25 kc will have a transmission loss $\cong$ 1 db.[48,52]

It will be recalled that the transmission loss is a measure of the total amount of energy removed by the dome from the main beam and diverted into other directions. The fraction of this energy reappearing in the direction of specular reflection depends on the specular reflection coefficient R. This coefficient gives the ratio of the dome-enclosed transducer response in the direction of specular reflection from the dome surface to that in the direction of the transducer axis. R depends on the transducer frequency and on the thickness and density of the dome wall. But R is also determined by the directivity of the transducer, by its position in the dome, and by the dome dimensions. Thus,

when $k_0a^2/4 < A$

$$R \cong 20 \log \left[\frac{\rho_1 d k_0}{2\rho_0} \cos\gamma\right]; \qquad (5a)$$

when $k_0a^2/4 > A$

$$R \cong 20 \log \left[\frac{\rho_1 d k_0}{2\rho_0} \cos\gamma\right] + 20 \log\left[\frac{F(x_{\parallel})}{x_{\parallel}}\right] + 20 \log\left[\frac{F(x_{\perp})}{x_{\perp}}\right]; \qquad (5b)$$

where

$$x_{\parallel} = \sqrt{\frac{k_0 a^2 \sec\gamma}{2R_{\parallel}}} \cong \frac{D}{L}\sqrt{\frac{2\pi a^2}{\lambda_0 D}};$$

$$x_{\perp} = \sqrt{\frac{k_0 a^2 \cos^2\gamma}{2R_{\perp}}} \cong \sqrt{\frac{2\pi a^2}{\lambda_0 D}} \quad \text{for torpedo-shaped domes,}$$

$$= 0 \quad \text{for straight-sided domes;}$$

$$\frac{F(x)}{x} \equiv \frac{1}{x}\left|\int_0^x e^{j\frac{\pi v^2}{2}}\,dv\right| \cong 1 \quad \text{for } x << 1,$$

$$\cong \frac{1}{\sqrt{2}\,x} \quad \text{for } x >> 1,$$

$$\leqslant 1 \quad \text{for all } x.$$

Here a is the *acoustic radius* of the transducer;[d] $R_{\parallel}$ and $R_{\perp}$ are the principal radii of curvature in the horizontal and vertical planes of the dome wall at the point of its intersection with the transducer axis; L and D are the maximum linear and transverse dimensions of an approximately ellipsoidal, torpedo-shaped dome or of a straight-sided dome with approximately elliptical cross section; A is the distance from the transducer diaphragm to the dome wall for the training position under consideration; and γ is the angle of incidence of the enclosed transducer's beam on the dome wall.[48,52]

It is now seen from an examination of equation (4) that the transmission loss of the dome is minimized when the thickness of the dome wall, the density of the dome material, and the frequency of the enclosed projector are as small as possible. These quantities should therefore be chosen accordingly, consistent with the mechanical strength of the dome wall, the seaworthiness of the wall material, and the directivity of the projector. In particular, the dome designer should use light metals such as aluminum and possibly organic materials like rubber;[e] shapes of maxi-

[c] The transmission loss is also roughly independent of the angle of incidence of the enclosed projector beam on the dome wall for angles of incidence less than 50°; for greater angles of incidence the transmission loss increases rapidly, because of propagation with appreciable amplitude of transverse elastic waves in the dome wall.

[d] The acoustic radius a is the radius of the rigid circular piston moving an infinite baffle having a beam width 2ϕ and a directivity index Δ equal to that of the actual projector [$1.42 \sin\phi = 0.61c/fa$, $\Delta \cong 20 \log (c/2\pi fa)$, see Chapter 4].

[e] Thus aluminum, various plastics, and stiff rubber strengthened mechanically by an expanded metal structure have all been used because of their relatively small density to minimize dome transmission losses and specular reflections. The seaworthiness of these materials, especially the first two, is open to question. It is claimed that aluminum easily corrodes in sea water; proper treatment of the metal may, however, render it salt water resistant.[40] Also, plastics are subject to aging and temperature effects. A stiff rubber structure may, however, turn out to be quite satisfactory.[63]

mum strength for given thickness should also be chosen, that is, the dome should be torpedo-shaped rather than straight-sided. Added strength can be obtained, if necessary, by expanded metal or possibly by corrugated sheet construction in preference to increased wall thickness.

It is seen from equations (5) that the specular reflection is not only minimized by minimizing the transmission loss but also is least for a given transmission loss when the projector is as directive as possible, the transverse dimensions of the dome are no larger than required to accommodate the projector, and the dome surface is as highly curved as possible, particularly in the vertical cross section.

In this last respect the doubly curved torpedo-shaped domes again have a decided advantage over the singly curved straight-sided domes. For example, at 25 kc, for a 40-mil thick torpedo-shaped dome of intermediate dimensions, the specular reflection is about 20 db below the main beam; for a straight-sided dome of the same sound window thickness and the same dimensions the specular reflection is only 10 db below the main beam.[48] In addition, the torpedo shapes have a considerable advantage from the standpoint of mechanical strength and streamlining.[25] Excessive noises due to eddying turbulence and to cavitation set in at much higher speeds for doubly curved torpedo-shaped domes than for singly curved straight-sided domes. Also, much of the self or ship's noise within a dome at supersonic frequencies, for a destroyer moving at relatively high speeds, arises from streaming turbulent water, particularly in instances where bubbles detached from the prow strike the dome and set the dome shell into vibration. This bubble noise is probably smaller for torpedo-shaped than for straight-sided domes because of the small front area and greater streamlining of the latter.

In regard to the effect of modern thin-wall (20 to 40 mil) stainless steel domes on echo ranging and listening, it may be shown that the decrease in the signal and the increase in the noise due to the dome transmission loss and the associated change in the directivity index affect detection ranges for various types of targets by relatively small amounts. A side lobe introduced by specular reflection in the directivity pattern may not be troublesome at first contact (except for a 60-mil, straight-sided dome), but it may give false bearings and thus make it difficult to regain contact at short range. The use of 20- to 40-mil stainless steel torpedo-shaped domes, with specular reflections 25–20 db below the main beam, overcomes this difficulty and in addition minimizes any mutual interference between beams from different craft.

9.2 BAFFLES[68]

The self noise picked up by a transducer on a moving vessel is due in part to turbulence and cavitation at the propeller screws; therefore, it might be expected that this noise is directional and has a maximum in the direction of the screws. For small vessels this is the case, necessitating additional acoustic shielding of the screws; on the other hand, on larger vessels the hull partially shields the transducer from the screws. The available information on the extent of acoustic shielding by the hull of various types of craft is meager; from the evidence at hand it seems desirable to provide additional shielding both on small and large vessels. On vessels where the self noise has a maximum in the direction of the screws, arising predominantly from propeller motion, such shielding will be advantageous. Even where noise is apparently nondirectional, a shield may lower the average noise level.[f]

A common method of acoustic shielding is to place a baffle inside the dome between the transducer and screws. There are two possible disadvantages in this method: First, sound incident on the transducer side of the baffle may be reflected to the transducer, increasing the noise level or giving spurious indications. This difficulty is eliminated by covering the front of the baffle with an absorbing material. The second disadvantage is the prevention of echo ranging or listening in the sector subtended by the baffle. Usually this is not a serious objection, since the baffle is always to the rear of the transducer and screw noise plus wake make it useless, in general, to listen or range toward the rear. In some cases the noise or echo of the submarine may be intense enough to be detectable in the rear sector; in this case the baffle actually prevents detection. This disadvantage may be great enough to offset any of the possible advantages of a baffle; the difficulty can be overcome by the use of an additional transducer without a baffle to sweep the rear sector.

[f] Nondirectional or isotropic self noise has been observed on large antisubmarine craft with dome-enclosed transducers shielded by baffles from the screws. Whether the noise still appears isotropic in the absence of the baffle is not known; if it does, the supposition that the noise arises largely from bubbles striking the dome obtains support.[40a]

The effectiveness of a baffle depends largely upon its material, its size and thickness relative to the sound wave length, and its location with respect to the transducer. When the problem of sound propagation past a baffle is considered, it is found that, for a plane wave incident on one side of the baffle, the pressure on the other side is due to both a transmitted wave and a diffracted wave. A sound shadow is formed behind the baffle only if the transmitted wave is small. The decibel ratio of the incident intensity to the transmitted intensity (through an infinite plane baffle) is called the transmission loss TL[g] and is given by Rayleigh's formula.[78]

$$TL = 10 \log \left[1 + \frac{1}{4}\left(\frac{\rho_0 c_0}{\rho_1 c_1} - \frac{\rho_1 c_1}{\rho_0 c_0}\right)^2 \sin^2 \frac{2\pi d}{\lambda_1} \right] \qquad (6)$$

where

TL = transmission loss,

ρ_0 = density of water,

c_o = sound velocity in water,

ρ_1 = baffle density,

c_1 = sound velocity in baffle material,

d = baffle thickness (or average thickness), and

λ_1 = sound wave length in baffle material.

This expression for TL versus d/λ_1 is plotted in Figure 2 for a plane parallel baffle of air (scale 1) and steel (scale 2) in water. It can be seen that a plate with a large loss at one frequency will also have a large loss over an extensive range of frequencies. The baffle thickness is not critical as long as it is not equal to a value appropriate to resonance transmission, that is, when $2d/\lambda_1$ is not equal to an integer. It is, therefore, not difficult to obtain a baffle with a large transmission loss; for example, a steel plate about 1 inch thick has a transmission loss of roughly 20 db at 24 kc. Thus, as far as transmission loss is concerned, such steel baffles are adequate; baffles containing air pockets are generally even more effective, the loss of a 0.2-inch thick air baffle at 24 kc being approximately 60 db.

Even when transmission loss is large, the infinitely long shadow of geometrical acoustics in which the sound intensity is zero is never formed behind the baffle. For incident plane waves of wave length λ in water, diffraction around the baffle edge limits the shadow to a length of approximately $\beta A/(\pi\lambda)$, where A is the area of the baffle projected on the wave front and β is a numerical factor $\cong 1$. (For a circular baffle

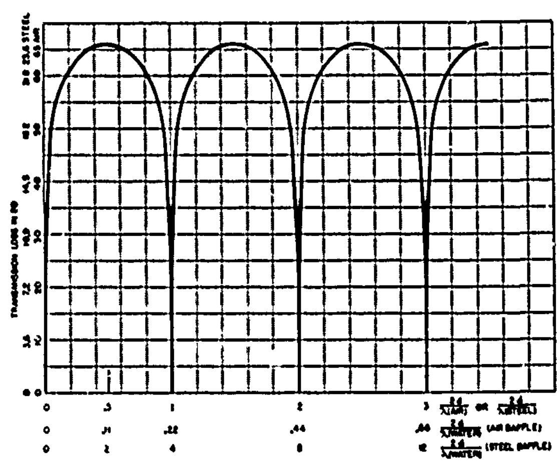


FIGURE 2. Transmission loss of baffles.

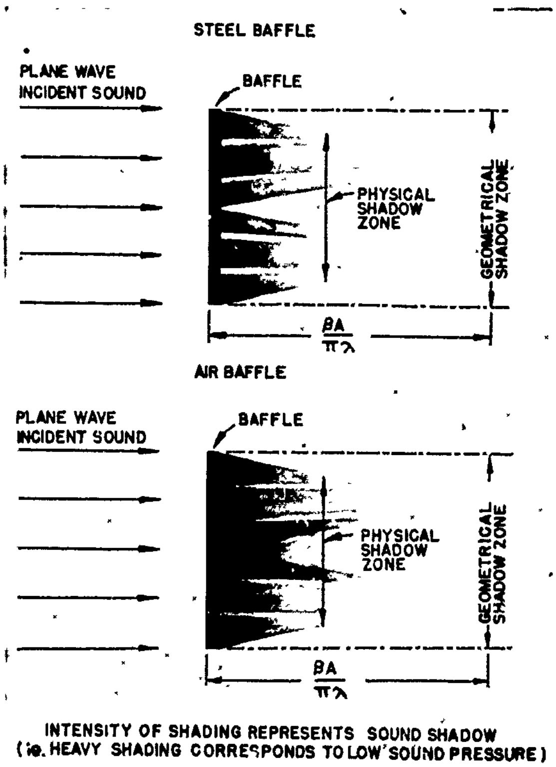
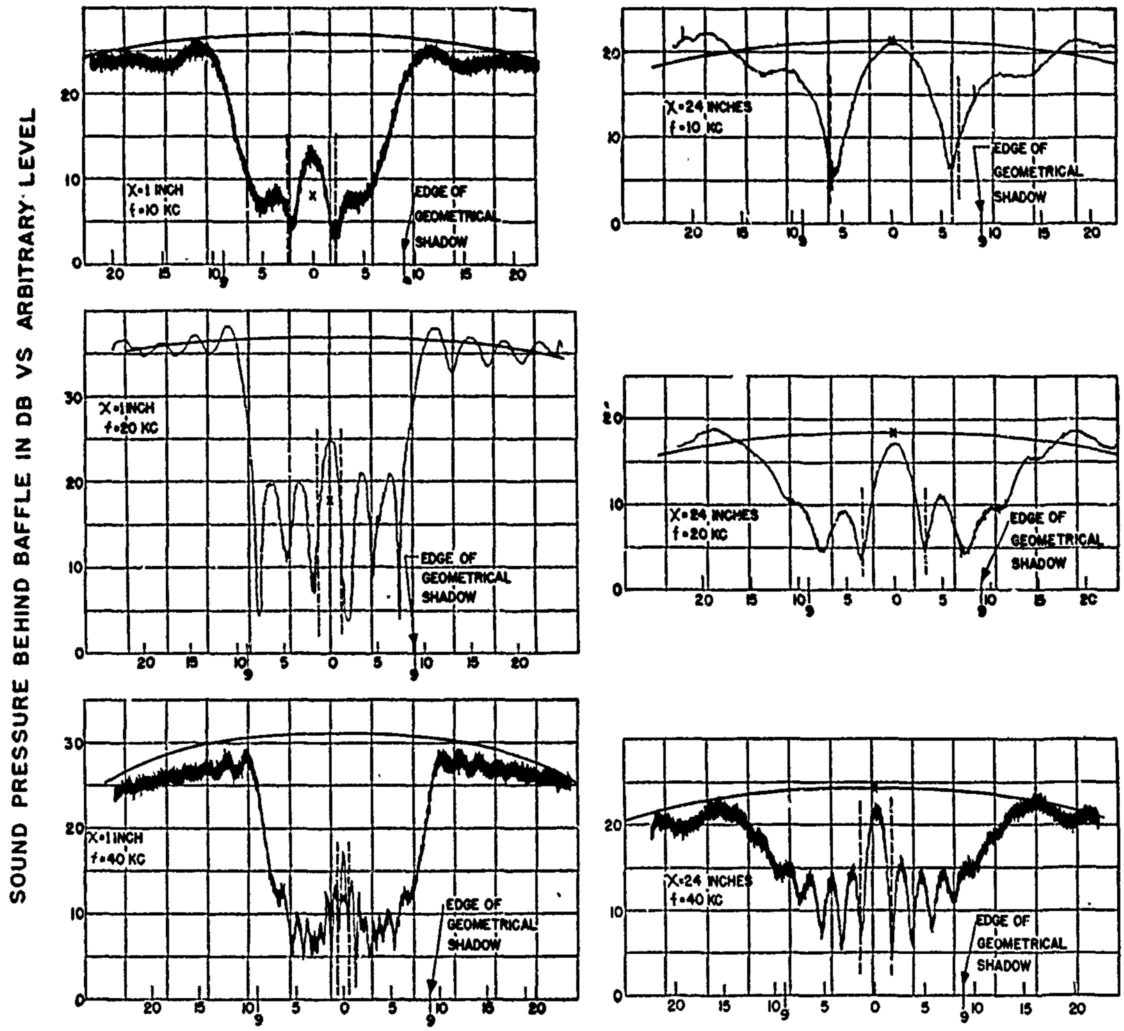


FIGURE 3. Sound pressure distribution behind baffle.

[g] Equation (6) reduces to equation (4) if $2\pi d/\lambda_1 \ll 1$ and $\rho_1 c_1/\rho_0 c_0 \gg 1$, conditions always satisfied by the thickness and material of dome walls in current use.



PERPENDICULAR DISTANCE FROM THE BAFFLE AXIS IN INCHES

VARIATION OF SOUND PRESSURE BEHIND 18" CIRCULAR BAFFLE
WITH PERPENDICULAR DISTANCE OFF THE BAFFLE AXIS

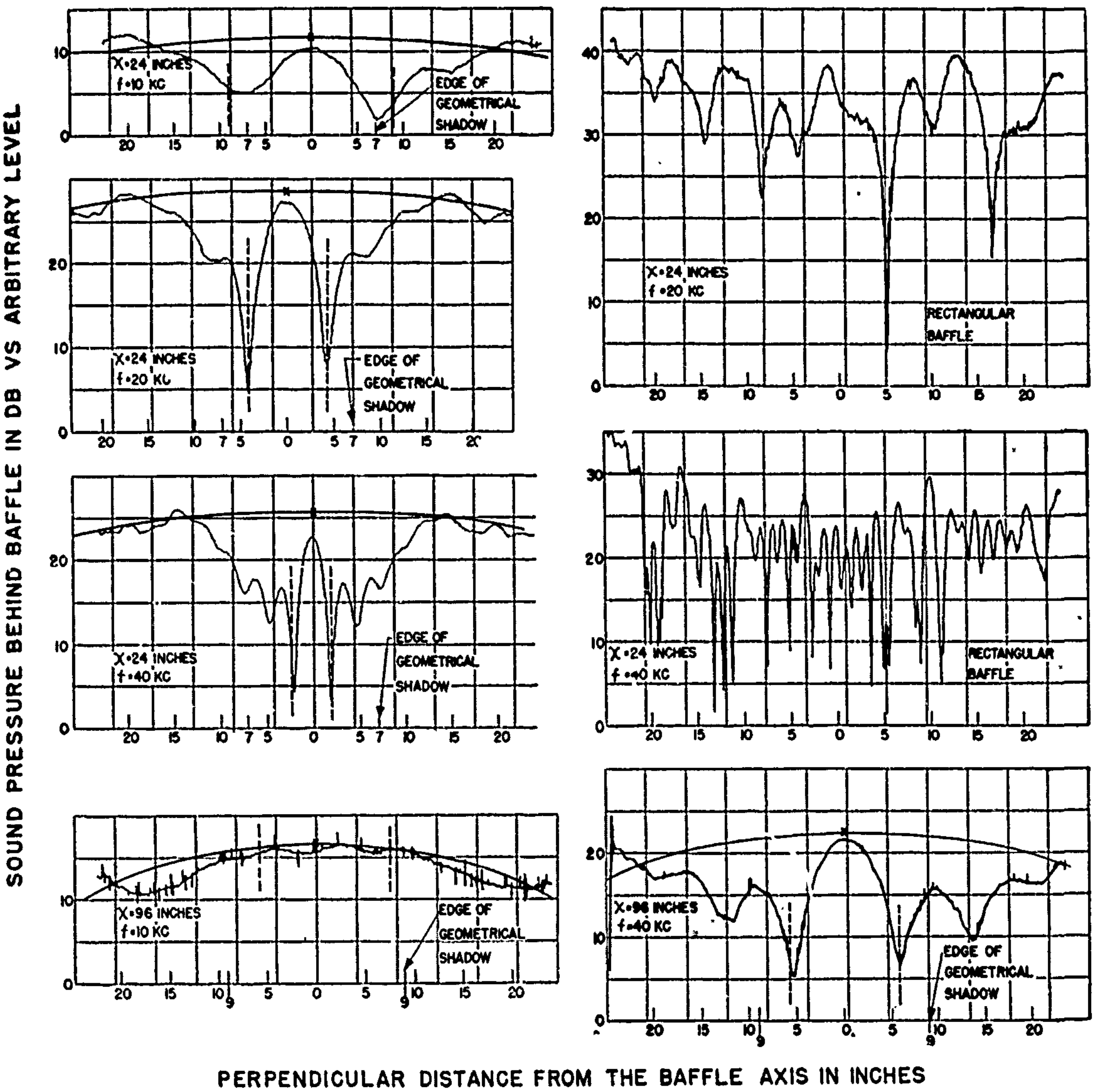
THE SMOOTH LINE ABOVE EACH PATTERN GIVES THE SOUND PRESSURE WITHOUT THE BAFFLE.

THE VERTICAL DOTTED LINES GIVE THE THEORETICAL POSITION OF THE "EDGES OF THE BRIGHT SPOT" i.e., OF THE PRESSURE MINIMA ON EITHER SIDE OF THE CENTRAL PRESSURE MAXIMUM.

THE CROSS GIVES THE THEORETICAL VALUE P_{AXIS}.

THE DISTANCE BEHIND THE BAFFLE AT WHICH THE PRESSURE IS MEASURED IS X; f IS THE FREQUENCY IN KC.

FIGURE 4A. Experimental variation of pressure behind baffles.



VARIATION OF SOUND PRESSURE BEHIND 14" & 18" CIRCULAR AND RECTANGULAR BAFFLES WITH PERPENDICULAR DISTANCE OFF THE BAFFLE AXIS

THE SMOOTH LINE ABOVE EACH PATTERN GIVES THE SOUND PRESSURE WITHOUT THE BAFFLE.

THE VERTICAL DOTTED LINES GIVE THE THEORETICAL POSITION OF THE "EDGES OF THE BRIGHT SPOT" i.e., OF THE PRESSURE MINIMA ON EITHER SIDE OF THE CENTRAL PRESSURE MAXIMUM.

THE CROSS GIVES THE THEORETICAL VALUE P_{AXIS}

THE DISTANCE BEHIND THE BAFFLE AT WHICH THE PRESSURE IS MEASURED IS X; f IS THE FREQUENCY IN KC.

FIGURE 4B. Experimental variation of pressure behind baffles.

calculations indicate that $\beta \cong 1.5$.)[68] The cross sectional area of the shadow is roughly A immediately behind the baffle and decreases to zero at a distance approximately $\beta A/(\pi\lambda)$ from the baffle. But even in the shadow region the sound pressure is not zero, the exact pressure distribution in the shadow depending upon the size, shape, and material of the baffle. Since the shadow of a circular disk baffle (air or steel) has been studied both theoretically and experimentally, it will be used as an example. Because of the symmetry of the circular baffle, the shadow is symmetrical about the axis. Thus, Figure 3, which shows the shadow region in a plane containing the axis, can be revolved about the axis to give a three-dimensional picture of the shadow region. The interference maximum on the axis—the "bright" spot—is due to the special symmetry of the circular baffle and would not be present if the baffle were another shape, such as rectangular.[h] On the other hand, the converging of the outer surface of the shadow due to the increase in size of an illuminated annular ring always occurs.

In addition to the bright spot, there are alternate bright and dark rings around the axis in any plane parallel to the baffle. Figure 4 shows the variation of pressure obtained experimentally[i] in the shadow of 18-inch and 14-inch diameter circular and 4x8 foot rectangular air-filled baffles along a line through the axis and parallel to the baffle diameter, at various distances from the baffle with 10-, 20-, and 40-kc sound. These patterns are in general agreement with theoretical expectations.[j]

Thus, for a baffle to be at all effective in shielding a transducer with a fairly large active face, that is, an echo-ranging projector, the baffle must have a large transmission loss (for example, $\geqslant 25$ db), must be considerably greater in area than the transducer, and must be placed appreciably nearer to the latter than $A/(\pi\lambda)$. To make this statement more precise, the effect of interposing a baffle between a transducer and a source is considered for two cases:

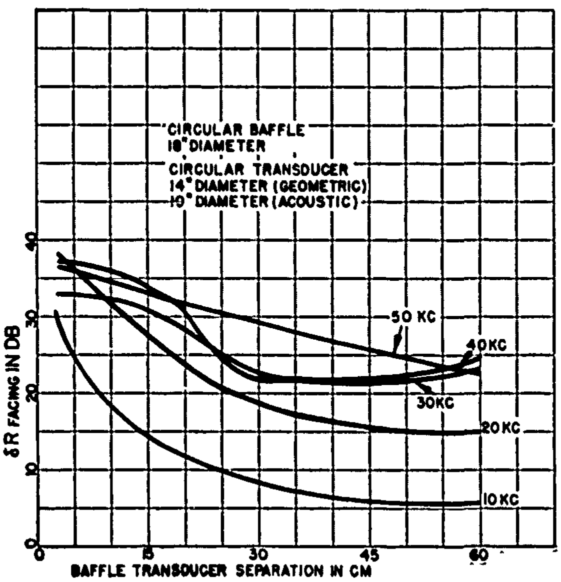


FIGURE 5. Decrease in front transducer response due to baffle.

1. The transducer faces the source: front transducer response.
2. The transducer faces away from the source: rear transducer response.

Case 2 is of practical interest, corresponding to the decrease in the rear response due to the baffle. Quantities applicable to cases 1 and 2 respectively are defined as follows:

δR = change in front transducer response due to baffle interposition,

$\delta R'$ = change in rear transducer response due to baffle interposition.

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[h] In the rectangular case, the energy previously concentrated by the circular baffle into the axis bright spot would be more or less uniformly distributed among several interference maxima within the shadow zone. Because of the "energy redistribution" the shielding effects of circular and rectangular baffles of comparable size on actual transducers (for example, the rather large echo-ranging projectors) are, at the distances used in practice, roughly equivalent.

[i] These patterns were obtained at the Orlando test station of USRL. The sound field was measured with a small size hydrophone so that the pressure at individual points in space was obtained.

[j] Thus, the variation of pressure p (within the shadow zone) with perpendicular distance y from the baffle axis, and at a distance x behind a circular baffle, is

$$p \cong p_{\text{axis}} J_0\left(\frac{2\pi y}{\lambda}\sqrt{\frac{A}{\pi x^2+\pi y^2+A}}\right) \exp\left[2\pi j\left(\frac{\sqrt{x^2+a^2+y^2}-x}{\lambda}\right)\right];$$

$$p_{\text{axis}} \cong p_{\text{inc}} \text{ for steel baffle}$$

$$\cong p_{\text{inc}} \frac{x}{\sqrt{x^2+\dfrac{A}{\pi}}} \text{ for air baffle}$$

for y not too close to the shadow boundary ($J_0 \equiv$ zero order Bessel function). See reference 68, equations (23) and (24). The theoretically expected values of p_{axis} and of the positions giving the edges of the bright spot are indicated on the diagram.

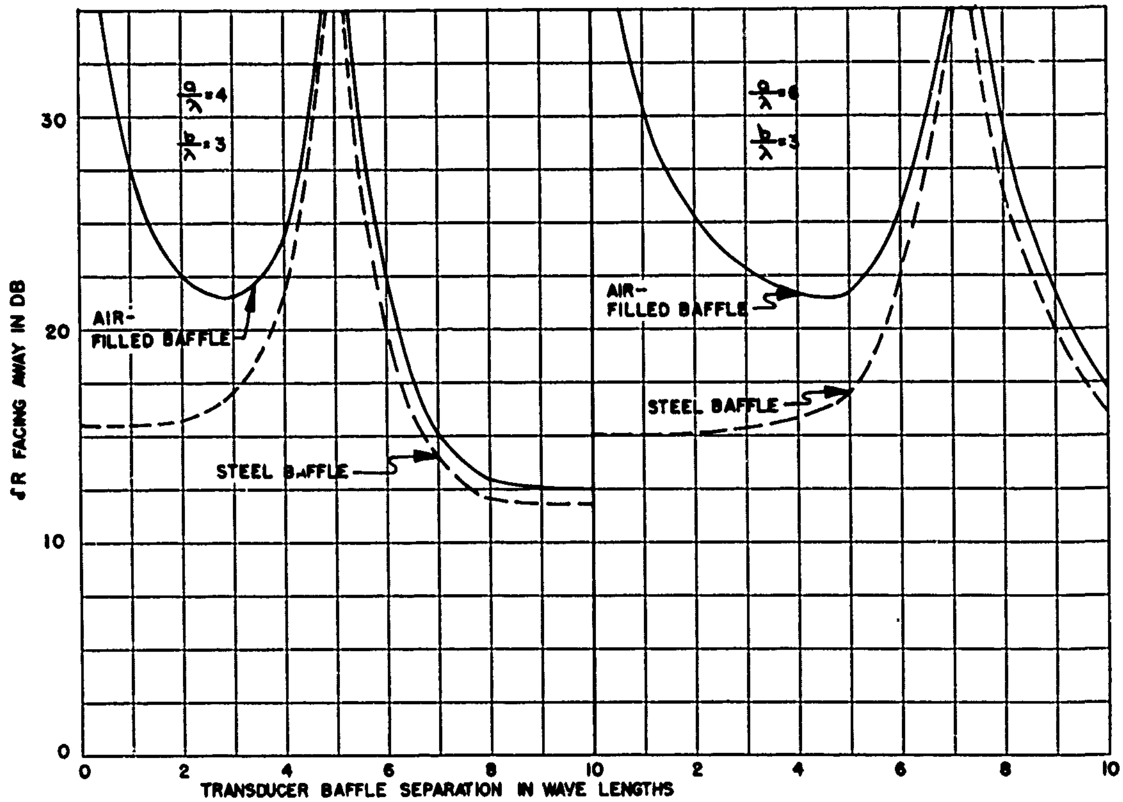

FIGURE 6A. Decrease in rear transducer response due to baffle.

Consider first δR. Figure 5 gives an experimentally obtained plot of δR versus separation between baffle and transducer for plane waves of various frequencies incident upon the former.[k] The baffle was air-filled, circular in shape, and had an 18-inch diameter; the transducer was also circular and had a 14-inch geometrical and a 10-inch acoustic diameter. It is seen that, in general, δR decreases with increasing separation; the values of δR, particularly those at the lower frequencies, are in rough agreement witn theory.[l]

Consider now the effect of interposing a baffle on the rear response of the transducer. Figure 6 (A, B, C) gives theoretically obtained plots of $\delta R'$ versus separation between baffle and transducer. The theory and the plots here reproduced indicate that an air-filled baffle with a transmission loss $\geqslant 25$ db decreases the transducer rear response by 15–25 db provided that the transducer-baffle separation x is considerably less than the smaller of the two critical lengths, $\pi ab/1.2\lambda$ and $8[(a-b)^2/\lambda + (a-b) + (\lambda/4)]$, where a is the radius of the baffle and b the acoustic radius of the transducer.[m] The first critical distance corresponds to the bright spot covering the rear of the projector, the second, to the annular ring on the rear making an important contribution.

It is seen from the above relations that for $a = b$, that is, for a transducer of the same size as the baffle, the baffle-transducer separation x must be less than 2λ to have any shielding at all. On the other hand, for $a = b$, and x as small as λ, the relations given are

[k] The data were obtained at the Orlando station of USRL.

[l] See reference 68, equation (44c):

$$\left|\delta R\right|^2 \cong \left|\frac{0.06\lambda^2 x\sqrt{a^2+x^2}}{a^2b^2}\right|^2 + \left|\frac{1}{2b}\left\{\left|b-a-\frac{\sqrt{2\lambda x}}{4}\right| + \left(b-a-\frac{\sqrt{2\lambda x}}{4}\right)\right\}\right|^2$$

where λ is the wave length, a the radius of the baffle, b the acoustic radius of the transducer, and x the transducer-baffle separation (air-filled baffle). Equation (44c) does not include the effect of the transmitted wave.

[m] The plots in Figure 6 are based on equation (47) of reference 68: $\delta R' \cong [x/(ab/\lambda)\,J_1(2.4\sqrt{a^2+x^2}/a)]$ for an air-filled baffle ($J_1 \equiv$ first order Bessel function; $x \ll \pi ab/1.2\lambda$ and $8\,[(a-b)^2/\lambda + (a-b) + \lambda/4]$. Equation (47) and the plots of Figure 6 do not include the effect of the transmitted wave.

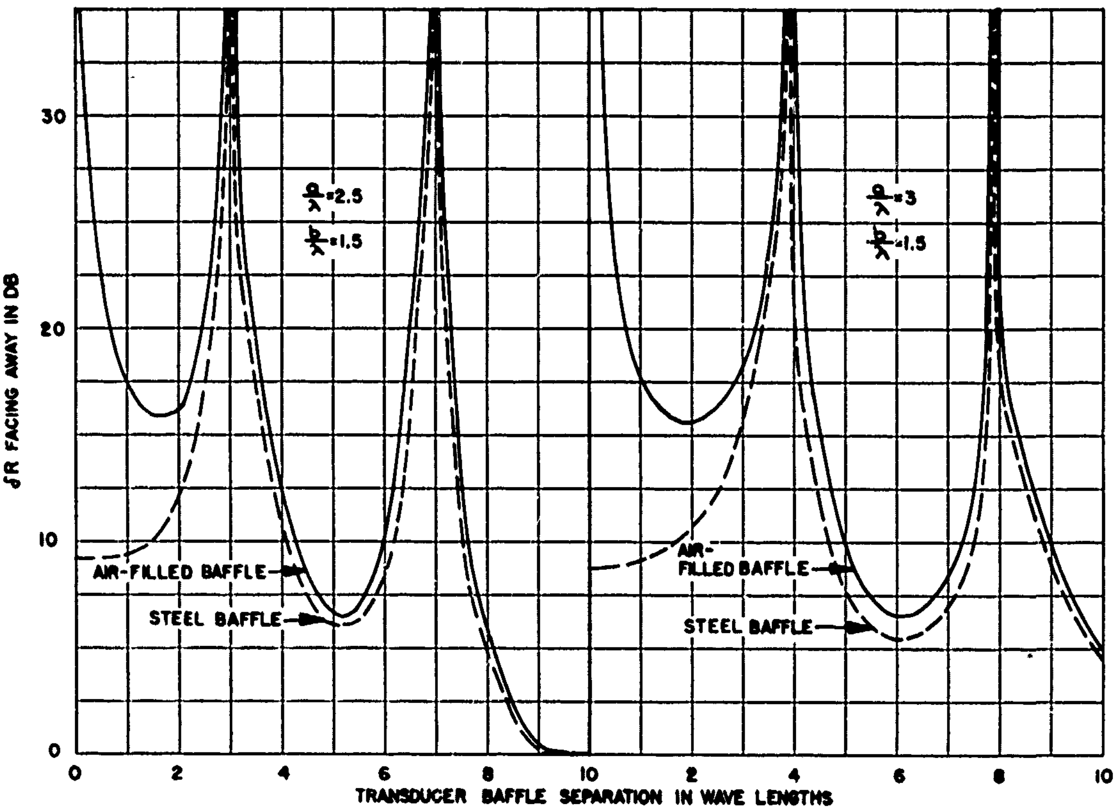

FIGURE 6B. Decrease in rear transducer response due to baffle.

no longer strictly applicable, and general considerations indicate that no shielding exists even for $x \leqslant \lambda$. On the other hand, Figure 6 indicates that for $a-b \gg \lambda$ the shielding is more or less independent of the exact value of $a-b$ and not too sensitively dependent on x as long as the latter is less than the smaller of the two critical lengths given above. However, with air-filled baffles the shielding is greatest for small separations.

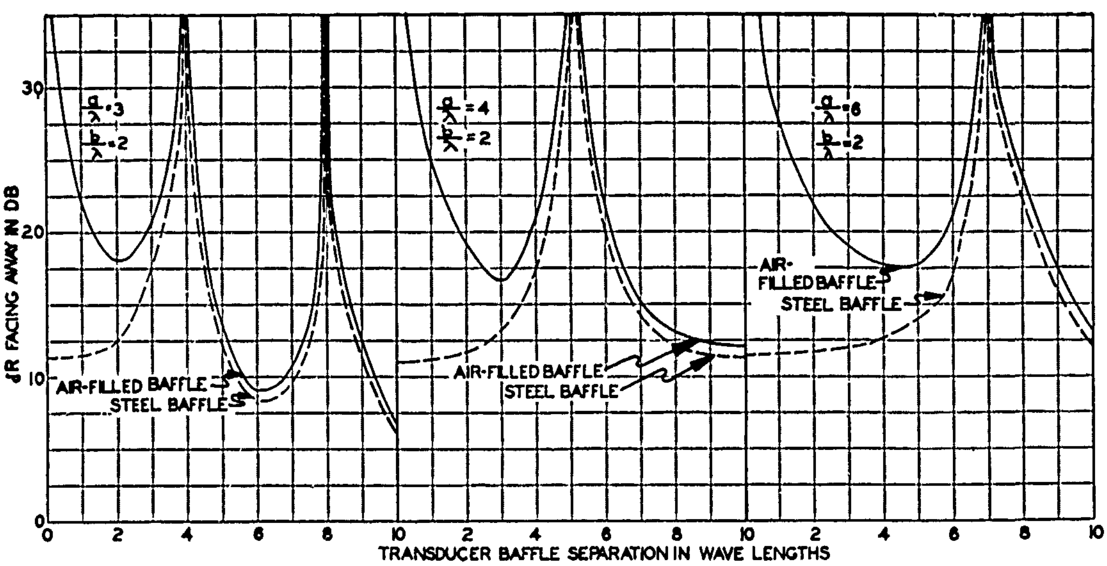

FIGURE 6C. Decrease in rear transducer response due to baffle.

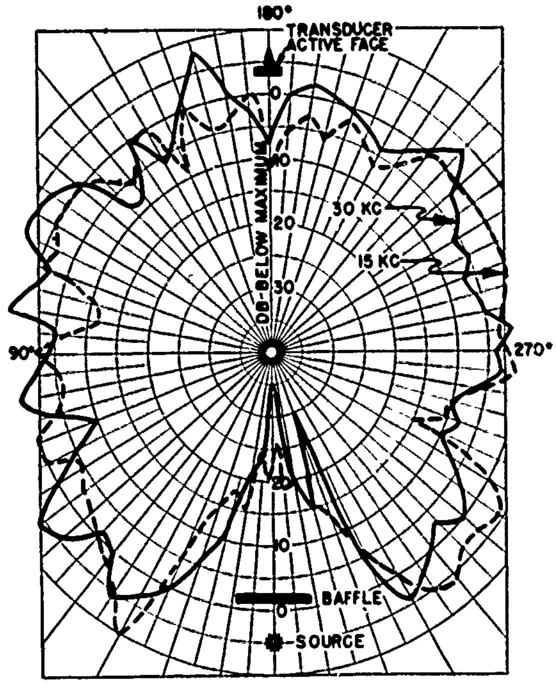

FIGURE 7. Change in response of dome-enclosed transducer due to interposition of baffle.

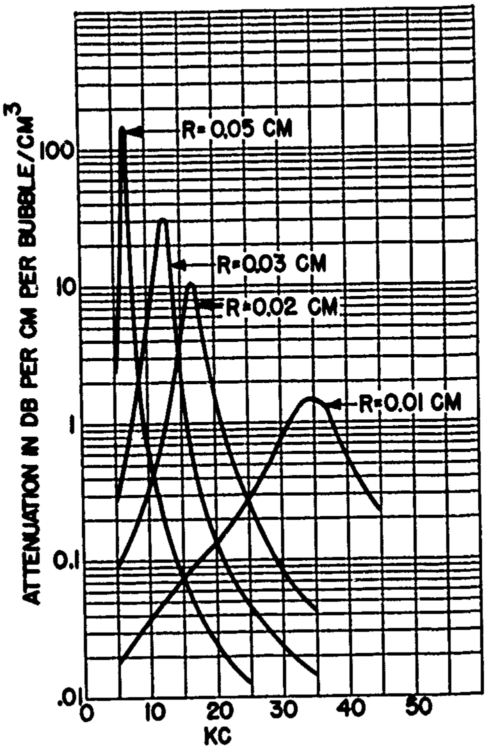

FIGURE 8. Attenuation versus frequency for different sized bubbles. (R = bubble radius.)

Few measurements have been made on the effect of a baffle on the rear response of a transducer, particularly for transducers enclosed in domes. Figure 7 shows the results of one such measurement. Referring to this figure it is seen that for angles between the transducer and dome axes varying from 90–270 degrees (180 degrees corresponds to the transducer facing away from the source) a 34x24-inch rectangular and dome-enclosed baffle gives an average decrease of only a few decibels in the response of a dome-enclosed transducer 20 inches away compared to the response of a *bare* projector at the same distance with no baffle interposed. These measurements, however, also include the detrimental effect of reflections from the dome wall which usually increase the response in the 90 to 270-degree sector by 5–15 db. Thus, in this case, the effect of the baffle more or less cancels that of the dome. Further experiments are particularly desired which will compare the rear response (angles of 90–270 degrees) of dome-enclosed and of bare transducers with and without a baffle.

Summing up, it has been shown that the diffraction of sound around, rather than its transmission through, the baffle limits the latter's effectiveness. Both with regard to transmission loss and to diffraction, air-filled baffles are superior to steel. To minimize the diffraction effect, the baffle should be appreciably larger than the transducer and should be placed as close as possible to it. The baffle-transducer distance should always be considerably less than the smaller of the two critical lengths given above.

9.2.1 Bubble Screens

It has been found that air bubbles resonate in water at frequencies depending on their size and that at and near that frequency they are very effective scatterers and absorbers of sound. When, then, a layer of such bubbles is inserted in the sound field, it offers very high attenuation. Such a layer may be used as a baffle and is called a bubble screen.

The propagation of sound through water containing bubbles has been studied by USRL both theoretically and experimentally.[54,56] The attenuation per centimeter thickness of a bubble screen varies directly as the number of bubbles per cubic centimeter. Fig-

ure 8 shows the attenuation versus frequency characteristics for different sizes of bubbles.

The use of bubble screens offers interesting possibilities, especially since, at least theoretically, it is possible by this means to intercept sound waves of certain frequencies while others are transmitted freely. The design and control of all these factors has not been fully worked out, but air bubbles fixed in space by means of an enclosing material are being used generally in sonar work. For instance, the effectiveness of air cell rubber as an acoustic shield depends on this principle.

Bubbles also have absorptive properties which are used in a bubble layer recently developed by the Massachusetts Institute of Technology.[65] This material has been applied by USRL as a lining for the high-pressure tank in order to obtain sound absorption at the walls. (See Chapter 6.) It is applicable for testing tanks generally and should find extensive use in production testing. (See Chapter 8.)

GLOSSARY

ACOUSTIC AXIS. Reference line adopted in transducer calibration, usually the direction of maximum response.

ADP. Ammonium dihydrogen phosphate crystal having marked piezoelectric properties.

A/S. Antisubmarine.

BAFFLE. A shield used to modify an acoustic path.

BATHYTHERMOGRAPH. An instrument which records the temperature of sea water as a function of depth.

BDI. Bearing deviation indicator.

BTL. Bell Telephone Laboratories.

CAVITATION. The formation of vapor or gas cavities in water, caused by sharp reductions in local pressure.

CREST FACTOR. In this volume, $\sqrt{2}$ times the ratio of peak-to-rms pressure of an acoustic wave.

CRYSTAL TRANSDUCER. A transducer which utilizes piezoelectric crystals, usually Rochelle salt, ADP, quartz, or tourmaline.

DDI. Depth deviation indicator.

DIRECTIVITY INDEX. A measure of the directional properties of a transducer. It is the ratio, in db, of the average intensity, or response, over the whole sphere surrounding the projector, or hydrophone, to the intensity, or response. on the acoustic axis.

DOME. A transducer enclosure, usually streamlined, used with echo-ranging or listening devices to minimize turbulence and cavitation noises arising from the passage of the transducer through the water.

ECHO REPEATER. Artificial target, used in sonar calibration and training, which returns a synthetic echo by receiving, amplifying, and retransmitting an incident ping.

ERSB. Expendable radio sono buoy.

HUSL. Harvard Underwater Sound Laboratory.

HYDROPHONE. An underwater microphone.

HYDROPHONE, VELOCITY TYPE. A pressure-gradient hydrophone.

MAGNETOSTRICTION EFFECT. Phenomenon exhibited by certain metals, particularly nickel and its alloys, which change in length when magnetized, or, (Villari effect) when magnetized and then mechanically distorted, undergo a corresponding change in magnetization.

MIT-USL. The Massachusetts Institute of Technology Underwater Sound Laboratory.

NDRC. National Defense Research Committee.

OSRD. Office of Scientific Research and Development.

PIEZOELECTRIC EFFECT. Phenomenon, exhibited by certain crystals, in which mechanical compression produces a potential difference between opposite crystal faces, or, an applied electric field produces corresponding changes in dimensions.

PING. Acoustic pulse signal projected by echo-ranging transducer.

PPI. Plan position indicator.

PRESSURE-GRADIENT TRANSDUCER. Transducer, such as a moving-ribbon hydrophone, in which the moving element responds to pressure difference rather than to pressure.

PROJECTOR. An underwater acoustic transmitter.

RADIO SONO BUOY. A buoy listening device that contains a hydrophone for receiving target signals and a radio transmitter for relaying the signals to patrolling air or surface craft.

RANGE RATE. Rate of change of range between own ship and target.

REAR RESPONSE. The maximum pressure within ±60 degrees from the rear of the transducer in db relative to the pressure on the acoustic axis.

ROCHELLE SALT. Potassium sodium tartrate ($KNaC_4H_4O_6 \cdot 4H_2O$) piezoelectric crystal used in sonar transducers.

SCANNING SONAR. Echo-ranging system in which the ping is transmitted simultaneously throughout the entire angle to be searched, and a rapidly rotating narrow beam scans for the returning echoes.

SEARCHLIGHT-TYPE SONAR. Echo-ranging system in which the same narrow beam pattern is used for transmission and reception.

SONAR. Generic term applied to methods or apparatus that use SOund for NAvigation and Ranging.

SPTU. Split projector test unit.

TRANSDUCER. Any device for converting energy from one form to another (electrical, mechanical, or acoustical). In sonar, usually combines the functions of a hydrophone and a projector.

USRL. Underwater Sound Reference Laboratories.

X-CUT. A cut in which the electrode faces of a piezoelectric crystal are perpendicular to an X or electrical axis.

Y-CUT. A cut in which the electrode faces of a piezoelectric crystal are perpendicular to a Y or mechanical axis.

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* BTL Bell Telephone Laboratories, Inc.
CUDWR-NLL Columbia University Division of War Research at the U. S. Navy Underwater Sound Laboratory.
CUDWR-SSG Columbia University Special Studies Group.
HUSL Harvard Underwater Sound Laboratory.
MIT-USL Massachusetts Institute of Technology Underwater Sound Laboratory.
UCDWR University of California Division of War Research at the U. S. Navy Radio and Sound Laboratory.
USRL Underwater Sound Reference Laboratories of Columbia University Division of War Research.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Numbers	*Name and Address of Contractor*	*Subject*
OEMsr-212	Western Electric Company (for Bell Telephone Laboratories, Inc.) 120 Broadway, New York, N.Y.	Studies and experimental investigations in connection with the development, construction and calibration of hydrophonic standard receivers and projectors and establish and operate field stations necessary for the maintenance of a calibration system.
OEMsr-20	The Trustees of Columbia University in the City of New York New York 27, New York	Studies and investigations and the development of methods and equipment pertaining to submarine warfare.
OEMsr-1130	The Trustees of Columbia University in the City of New York New York 27, New York	Studies and experimental investigations in connection with the testing and calibration of acoustic devices including operations of underwater sound reference test laboratories.
OEMsr-783	Western Electric Company (for Bell Telephone Laboratories, Inc.) 120 Broadway, New York, N.Y.	Studies and investigations in connection with the development of calibration devices and methods in the fields of hydrophonics, etc.
OEMsr-1189	Western Electric Company (for Bell Telephone Laboratories, Inc.) 120 Broadway, New York, N.Y.	Manufacture, stocking and repair of hydrophonic apparatus.

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the Navy Department through the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
NS-139	Testing and calibrating facilities
NS-182	Projector requirements and test limits

HYDROPHONE ADVISORY COMMITTEE

The Hydrophone Advisory Committee was the name which soon came to be used for the Committee on Standards and Calibration appointed by the Coordinator of Research and Development, April 1942, for the following purpose: to assist in establishing calibration techniques, reference levels, and standard definitions and terms to be used generally by all groups making underwater sound measurements of interest to the Navy.

Shortly after the organization of this committee, Dr. Robert S. Shankland was selected to be its chairman. While from time to time the personnel of the committee changed, in general the following organizations were represented at meetings and were otherwise active:

Office of the Coordinator of Research and Development (now Office of Research and Inventions)
Bureau of Ships (940)
Naval Ordnance Laboratory
Naval Research Laboratory
Division 6:
- Columbia University Division of War Research at the U. S. Navy Underwater Sound Laboratory, Harvard Underwater Sound Laboratory, Massachusetts Institute of Technology Underwater Sound Laboratory, University of California Division of War Research at the U. S. Navy Radio and Sound Laboratory, Underwater Sound Reference Laboratories of Columbia University Division of War Research

Bell Telephone Laboratories, Inc.
Brush Development Company
Radio Corporation of America
Submarine Signal Company

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.

AUTHOR(S) (and others)

Shankland, R. S.
Foldy, Leslie I.
Gregg, Earle C.
and others

DIVISION: Electronics (3)
SECTION: Testing (11)
CROSS REFERENCES: Sonar equipment - Calibration methods (87475)

ATI- 15826
ORIG. AGENCY NUMBER
Vol-10
REVISION

AMER. TITLE: Basic methods for the calibration of Sonar equipment

FOREIGN TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D.C.

TRANSLATION:

COUNTRY	LANGUAGE	FOREIGN CLASS	U.S. CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	180	144	photos, tables, diagrs, graphs

ABSTRACT

Testing methods and apparatus developed while carrying through an extended program of precision measurements on underwater acoustic devices are discussed. The basic principles of the measurements are developed and systematized in close coordination with a description of the measuring and calibration facilities of the Underwater Sound Reference Laboratories at Mountain Lakes, New Jersey, and Orlando, Florida.

ATI- 15827

ORIG. AGENCY NUMBER

REVISION

Foldy, Leslie L.

AUTHOR(S)

DIVISION: Electronics (3)
SECTION: Testing (11)
CROSS REFERENCES: Sonar equipment - Calibration methods (87475)

AMER. TITLE: Operation and application of underwater sound devices

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N. CLASS	U. S. CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	5	5	diagrs

ABSTRACT

Calibration work in underwater sound is concerned primarily with electroacoustic transducers. According to the nature of physical processes used in the energy conversion, transducers may be classed as electrodynamic, electrostatic, piezoelectric, and magnostriction transducers. Tactical application of the device includes the detection of surface vessels, submarines, and underwater phenomena by surface vessels and submarines. Nontactical applications include: fathometer depth determination by surface craft and submarines; underwater communication by code and voice; and calibration of sonar gear with standard projectors and hydrophones.

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CTED

ROLL FORM (10 JAN 47)

Foldy, Leslie L.
Primakoff, H

AUTHOR(S)

DIVISION: Electronics (3)
SECTION: Components (10)
CROSS REFERENCES: Transducers, Sonar (95127)

ATI- 15828
ORIG. AGENCY NUMBER

REVISION

AMER. TITLE: Generalized theory of electroacoustic transducers

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D.C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	7	1	diagr

ABSTRACT

A generalized theory of linear passive electroacoustic transducers is developed. Only those transducers are considered in which the acoustically active part of the surface, the diaphragm, vibrates in such a manner that its normal velocity is the same at all points. Formulas are developed for electroacoustic transducers in which the diaphragm vibrates rigidly; for relationships which obtain when an electroacoustic transducer is coupled to electric elements or to a medium capable of propagating sound; for determination of effective impedances, and for determination of the sensitivities of transducers.

TSDIN FORM 69 (13 MAR 47)

AUTHOR(S): Dietze, Eginhard

DIVISION: Electronics (3)
SECTION: Testing (11)
CROSS REFERENCES: Sonar equipment - Calibration methods (87475)

ATI- 15829
ORIG. AGENCY NUMBER

REVISION

AMER. TITLE: Types of acoustic measurements

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	16	10	diagrs, graphs

ABSTRACT

Types of acoustic measurements are discussed. The pertinent physical characteristics that should be measured in a calibration test on an echo-ranging projector are directivity, frequency-response characteristics, power output, selectivity, threshold pressure, receiving response, and impedance. Terms are explained and formulas developed.

Foldy, Leslie L. AUTHOR(S)	DIVISION: Electronics (3) SECTION: Testing (11) CROSS REFERENCES: Sonar equipment - Calibration methods (87475)	ATI- 15830 ORIG. AGENCY NUMBER REVISION

AMER. TITLE: Testing technique

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	38	16	diagrs, graphs

ABSTRACT

The testing of underwater sound devices assumes two forms, calibration tests and operational tests. Most calibration measurements underwater sound equipment consists of measurements on transducers. Means are indicated by which one may determine the true values of the quantities measured. Choice of site, elimination of reflectione, choice of testing geometry, establishment of sound fields and calibration of devices covering wide frequency ranges are treated in detail.

MAY 1948

RESTRI

ATI- 15831

ORIG. AGENCY NUMBER

REVISION

RDC FORM (10 FEB 47)

Hartmann, Erhard
Gregg, Earle C.

AUTHOR(S)

DIVISION: Electronics (3)
SECTION: Testing (11)
CROSS REFERENCES: Sonar equipment - Calibration methods (87475)

AMER. TITLE: Description and operational procedures of the USRL test stations

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	70	82	photos,tabls,diagrs,graphs

ABSTRACT

Description is given of the Mountain Lake Test Station of the Underwater Sound Reference Laboratories. Calibration and testing equipment, and procedure are discussed in detail, implemented by graphs and photographs. In addition, a brief survey is made of the Orlando Test Station. Recommendations are presented for improvements of the USRL Test Stations.

ATI- 15832

ORIG. AGENCY NUMBER

REVISION

(10 NO 97)

Dietze, Eginhard
Leighton, L. P.

AUTHOR(S)

DIVISION: Electronics (3)
SECTION: Testing (11)
CROSS REFERENCES: Sonar equipment - Calibration methods (87475)

AMER. TITLE: Computation from test data

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D.C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	11	21	tables, diagrs, graphs

ABSTRACT

Method of computing the calibration of an underwater instrument from test data is described. Computation is made of receiving response, threshold and impedance, transmitting response, and reciprocity calibration of standards. Equations are developed and examples given.

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RDC FORM O (13 FEB 47)

AUTHOR(S)		ATI- 15833
Shrader, Erwin F.	DIVISION: Electronics (3) SECTION: Components (10) CROSS REFERENCES: Transducers, Sonar (95123)	ORIG. AGENCY NUMBER REVISION

AMER. TITLE: Production testing of sonar transducers

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	4	2	diagrs

ABSTRACT

Production testing of sonar transducers falls into two parts: tests of physical strength, watertightness, and polarity of electrical elements, and acoustic measurements of directivity, response, and impedance. For a complete description of a sonar transducer, it is necessary to know the receiving and transmitting response as a function of frequency, and the directivity patterns at several frequencies in one or more planes depending on the symmetry of the device. Requirements for each measurement are discussed.

ROLL NO. (NO.)

AUTHOR(S)		
Primakoff, Henry Keller, Joseph B.	DIVISION: Electronics (3) SECTION: Components (10) CROSS REFERENCES: Transducers, Sonar (95123)	ATI- 15834 ORIG. AGENCY NUMBER REVISION

AMER. TITLE: Acoustic equipment associated with underwater sound devices: Domes and baffles

FORG'N. TITLE:

ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 6, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	1946	13	11	diagrs, graphs

ABSTRACT

Calibration of acoustic equipment auxiliary to electroacoustic transducers is described. Among the most important auxiliary equipment tested were streamlined domes and baffles. Transmission loss and specular reflection induced by a dome of given material, wall thickness, and dimensions, on an enclosed transducer of given frequency, directivity, and position within the dome are calculated. Effectiveness of baffles is determined by means of equations.